PROTOTYPE PROPELLANT-TESTING SYSTEM

PHASES I AND II - FEASIBILITY STUDY AND PRELIMINARY DESIGN

TECHNICAL DOCUMENTARY REPORT NO. RTD-TDR-63-3
February 1963

Rocket Propulsion Laboratories
Research and Technology Division
Air Force Systems Command
United States Air Force
Edwards, California

Air Force Program Structure No. 650A
AFSC Project No. 3850, Task No. 385003

NOTICES

FOREWORD

This report was prepared by the Chemical Products Division of Aerojet-General Corporation under USAF Contract No. AF 04(611)-8196. This contract was initiated under Program Structure No. 650A, Project No. 3850, Task No. 385003. The work was administered under the direction of the Rocket Propulsion Laboratories, Air Force Systems Command, with Mr. R. A. Biggers (DGPCS) acting as project engineer and Mr. A. V. Jensen (DGPC) as senior engineer, 6593d Test Group (Development).

The report covers work conducted from 14 May 1962 through 30 November 1962 and is the final report on Phases I and II of the program. It is submitted in partial fulfillment of the contract, is catalogued by Aerojet-General as Report No. 2452, and was prepared in accordance with Air Force Systems Command Manual 5-1 (AFSCM 5-1), as specified by the contract.

ABSTRACT

The feasibility of constructing a test system for studying dynamic effects in liquid-propellant streams was examined and a prototype system was designed that is acceptable for use with storable, corrosive, or cryogenic fuels and oxidizers. Recommendations are made for on-stream analyzers suitable for the monitoring of a wide range of physical and chemical properties of dynamic systems. A contaminant-addition system was designed to provide propellant of a known contamination level for subsequent tests.

This technical documentary report has been reviewed and is approved.

A. V. Jensen (DGPC)
Senior Engineer

R. A. Biggers (DGPCS)
Project Engineer

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I. INTRODUCTION

Large quantities of propellants are transferred routinely from the shipping vessel to holding tanks and then to the missile. In all these transfers, the propellant is subjected to contamination from many sources: corrosion of the transfer lines and test articles, exposure to the atmosphere, accidental addition of contaminants, and propellant decomposition. The prototype propellant-testing system under consideration in this program would be compatible with a wide, representative variety of propellants and would make possible the preparation of contaminated propellant for laboratory examination and analysis under dynamic conditions.

This report covers Phases I and II of the program. Phase I consisted of a feasibility study, and Phase II the development of design considerations for the propellant-test system and contaminant-addition system. Phase III, which will be covered in a subsequent report, includes the construction of a prototype contaminant-addition system.

II. OBJECTIVES AND SUMMARY

The purpose of the work in Phase I was to determine the feasibility of the prototype-propellant-test-system concept. Specific areas of study were (a) the tank, transfer, and test system, (b) on-stream analyzers, and (c) the contaminant-addition system. As much as possible, it was the goal of the study to incorporate commercially available components into the test system. The data resulting from this survey are summarized in Tables 1 through 29, and the names and addresses of the manufacturers surveyed (and, in some cases, their representatives) are presented in Table 30.

Requirements to be fulfilled by the tank, transfer, and test system were designed to give flexibility to the prototype unit. Consideration was given to a system compatible with liquid oxygen, liquid hydrogen, liquid fluorine, hydrazine, nitrogen tetroxide, pentaborane, tetrafluorohydrazine, hydrogen peroxide, and chlorine trifluoride. The system is adaptable for material-compatibility studies and flow filtrations, as well as a variety of analyses. It is also capable of performing tests that include, but are not limited to, the use of rapid-scanning infrared absorption, ultraviolet absorption, radio-frequency spectroscopy, activation analysis, conductivity measurements, and photographic observation. The general test parameters of the system include propellant temperatures from -420 to +200°F, a pressure range from vacuum (a few microns of mercury) to 215 psig, and a flow-rate range from 5 to 150 gal/min (gpm) through the test section. The two vessels used as holding tanks are capable of handling cryogenic propellants in the inner vessel with a maximum loss of nitrogen of 2%/day. It should be possible to introduce into the propellants metered amounts of gaseous and liquid impurities having a normal boiling point below -150°F. Provision is incorporated for weighing these vessels during propellant transfer, in addition to providing venting, filling, pressurization, recirculation, liquid-level control, liquid-temperature measurement, and propellant and vent-gas disposal.

Certain specific requirements are met. Compatible materials of construction are incorporated in the entire system. Capability is provided to evacuate the test system to 4×10^{-4} torr at the rate of 1500 liters/sec; line or vessel jackets utilizing liquid-nitrogen coolant are capable of

evacuation. An important part of Phase I was the generalized study of a contaminant-addition system capable of providing a source of propellant containing known amounts of contaminants. Methods of operation and equipment were developed that assure the delivery of uniform dispersions or solutions of contaminants to test articles under flow conditions. The contaminants to be added include, but are not limited to, gaseous or liquid methane (15 to 3000 parts per million, ppm), gaseous or liquid nitrogen (160 to 5000 ppm), gaseous carbon dioxide (10 to 5000 ppm), water vapor (10 to 50 ppm), liquid water (10 to 1000 ppm), flake iron oxide (1 to 50 mg/gal), and specially sized silicon dioxide (1 to 50 mg/gal). The accuracy of contaminant addition ranges from 6 to 20%, depending on the amounts and concentrations. The contaminant is added at a rate that assures uniform mixing throughout the vessel within 15 min or less.

Phase II, in which assembly and flow diagrams and initial drawings of the propellant test system were prepared, was based on the Phase I feasibility study.

Phase III, to be covered in a subsequent report, will include the construction of a prototype contaminant-introduction system for use as a proven component of the prototype system for the testing of chemical and physical properties. Engineering drawings and operation procedures for this component will be developed as the work progresses. The system will be evaluated after construction, using liquid nitrogen as a typical cryogenic fluid. Operation of the individual units will be demonstrated using gaseous, liquid, and solid contaminants.

III. ENGINEERING STUDIES

The design and construction of a versatile test system capable of circulating and processing presently used liquid propellants with high reliability involves careful attention to all equipment details. The chief design problem for the contemplated assembly centers about the pumping of any of the propellants, which boil at various temperatures in a $600^{\circ}F$ range, at a variable rate of up to 150 gpm. The need for maintaining a known and constant level of contamination, while providing access for devices for continuous monitoring of the physical condition of the propellant, further complicates the design effort. The detailed effects of propellant handling and testing were examined, and the results are presented below.

A. DESIGN CONCEPT

1. System Configuration

The variety and nature of the liquids to be processed in the proposed system suggest that the simplest possible circuit would be the most likely to provide an ultimately successful installation. Basically, this would require a propellant-storage vessel, piping to the analytical instruments, and return piping to the vessel. The system as proposed approaches this level with what is considered to be the minimum amount of interference with flow, consistent with the specified capabilities of the propellant-testing system.

The primary purpose of the system is to perform analytical measurements under normal propellant-flow conditions. The functional stipulations include filtration, visual or photographic observation of flow and test coupons, operation at either high or low temperatures and under pressure or in a vacuum, and operation with added contaminants. Additionally, provisions are to be incorporated for weighing the propellant vessel, venting, filling, pressurization, recirculation, liquid-level control, liquid-temperature indication, and propellant and vent-gas disposal.

Some of the experiments will require exposure to the full stream flow, and others will require only a small representative flow; hence, side streams are required to provide propellant samples at low flow rates. Other instrumentation can be included in the main stream, where up to 150 gpm may be circulated for tests. In either case the analyzed propellant is transferred back to the original supply vessel, or may be transferred to a similar holding tank if mixing of the analyzed fluid with the supply fluid is not desired, as might be the situation when a filtration is performed.

Figure 1 provides an overall schematic view of the propellant-testing system as designed. Additional tank and piping details are shown in succeeding figures.

2. Transfer Method

Propellant transfer is resolved into two methods: pumping or gas pressurization. If pressurization were used exclusively, it would be necessary to transfer from one tank to the other and thereby limit the time available for an experiment. At a maximum flow of 150 gpm, the test duration would be approximately 1 min, allowing some time for flow equilibrium to be reached and thereby severely reducing the capabilities of the system. In addition, solubility of the pressurizing gas might complicate the test results. Alternatively, the pumping of some of these propellants has presented definite problems in the past; for others, there is essentially no experience with pumping. After thorough evaluation of pumping data it was concluded that both transfer systems would be included, but with the intention of primarily using a pump for all propellants.

The general use of pumps poses the problem of cavitation and two-phase flow for high-vapor-pressure liquid transfer. This can be partially compensated for by pump design. However, operating the system under pressure would be more effective, and, as the pressure-transfer system is to be included, the necessary equipment would be present. For propellants with which pressurized operation would not be permissible, or where a partial vacuum might be desired, it is proposed to introduce a positive head at the pump by elevating the propellant-containment vessels.

3. Piping System

Establishment of the piping layout immediately presents all the problems inherent in the testing system. A temperature range from -423 to +200°F introduces expansion and contraction problems. Vacuum tightness, corrosion resistance, and velocity requirements further restrict the design. The initial problem was to determine whether one piping system is feasible or

whether parallel systems must be included (depending on the propellant properties) and, if so, the number of parallel systems needed. It was concluded that the minimum piping necessary requires a parallel circulation system for liquid hydrogen (LH_2), while the balance of the propellants can be suitably processed in a common system. The design requirements of the parallel system will permit the use of one pump suction line for all propellants and interchangeable use of the side stream branches. The proposed system of vacuum-jacketed piping is shown in Figure 2.

The principal factors affecting piping layout may be exemplified by considering only LH_2, liquid fluorine (LF_2), and pentaborane (B_5H_9). Liquid hydrogen must be transferred in vacuum-jacketed equipment to provide suitable thermal insulation. Fluorine should be transferred in an insulated system, and pentaborane requires no insulation. Hydrogen and B_5H_9 are not considered corrosive, however, and the materials of construction are not seriously limited. Fluorine is very corrosive under most conditions, and there are only a few acceptable materials. Liquid densities and viscosities vary by a factor of more than 20. These parameters significantly affect the pressure drop through the transfer system, frictional effects, and horsepower requirements. Piping concepts can be reduced to five workable systems, as follows:

a. LH_2 - Vacuum-jacketed, small pipe diameter, pumped, general compatibility

b.   Liquid oxygen (LO_2), liquid nitrogen (LN_2) - Vacuum-jacketed, large diameter, pumped, general compatibility

c. LF_2 - Bare piping, large diameter, pumped, limited compatibility

d.   Hydrazine (N_2H_4), nitrogen tetroxide (N_2O_4), hydrogen peroxide (H_2O_2) - Bare piping, large diameter, pumped, moderate compatibility

e. B_5H_9, tetrafluorohydrazine (N_2F_4), chlorine trifluoride (ClF_3) - Bare piping, large diameter, pressurized transfer, limited compatibility.

Each of these systems would optimally be equipped with a separate pump or pressure-transfer device, thus providing optimum mechanical efficiency, material compatibility, and flow control. Liquid hydrogen, because of its low density, must be pumped at a higher velocity than the other propellants in order to keep any entrained solid contaminants in suspension. A hydrogen pump will also normally require a higher impeller speed to develop a given head because of the low density of hydrogen.

As for other cryogenic liquids, the LO_2 system should be insulated because a relatively small quantity of the liquid is being recirculated through a long line and heat transfer would become intolerable for an extended run under bare-line conditions. Liquid fluorine would be more safely transferred in bare lines to provide maximum control over possible

leakage and breakdown, but excessive volatilization would occur. Other than for structural materials, the LO_2 and LF_2 pumps could be the same. The fluorine system is much more limited than the oxygen system with regard to possible materials of construction.

Hydrazine, N_2O_4, and H_2O_2, although differing somewhat in physical properties, are sufficiently similar to be handled in a single system. Because N_2H_4 and H_2O_2 are subject to catalytic decomposition, the possible structural metals are more limited than for N_2O_4. These propellants may be transferred by systems of normal construction using a pump similar to those suitable for LO_2.

Pentaborane, N_2F_4, and ClF_3 are usually transferred by pressurization. An uninsulated piping system is advantageous for the reasons given for fluorine. Experience with the pumping of these fluids is limited but it appears that they could also be transferred by a pump suitable for LO_2 if consideration is given to the compatibility of metals.

Five systems as described above, operating from central supply tanks, would obviously be unwieldy and expensive. It is apparent that, if compatible materials could be found, the last three systems could be consolidated into one. If these propellants could also be safely handled in a vacuum-jacketed system, only two systems would be needed, which would provide a much more practical installation. The reliability of internal connections without obstructions and dead spots is the prime criterion for the use of jacketed systems with fluorine; otherwise, the insulating properties would be very advantageous. Consultation with manufacturers of such piping indicates that jacketed systems can now be assembled that will provide the necessary soundness of construction. These systems can be fabricated from most useful metals and with a wide variety of joining methods.

To avoid the cost, assembly, and inspection problems of vacuum jacketing, it is possible to use a trough or open channel surrounding the propellant piping, which can be filled with LN_2 when low temperatures are required. The nitrogen consumption would obviously be high but the system has merit if only short-term operations are to be encountered.

4. Insulation

The initial concept of thermal shielding was oriented toward foam-insulated piping and double-walled superinsulated vessels. In addition, much has been published on the use and advantages of uninsulated transfer systems for propellant handling, with the general conclusion that insulation is frequently not of significant value. The salient feature of the presently proposed system is the recirculation capability, however, and heat gain could be excessive under many conditions of operation, because no limiting time has been established for the recirculation period. The most obvious effect would be flash vaporization of cryogenic liquids in circulation, resulting in two-phase flow, which would negate flow-meter readings and some types of analytical measurements, such as nephelometry. Apparently, insulation must be used.

Bulk-insulated piping would require considerable precooling before each experimental run with cryogenic fluids. Although this would not

be a major obstacle, it would encumber dismantling of the system and conceal leaks, which would be of significance because it is expected that frequent disassembly will be necessary and leakage of any type will be hazardous. A vacuum-jacketed piping system could be designed for relatively easy dismantling and could be instrumented to simplify leak detection, as previously noted.

If multiple-shield insulation were to be used in the jacket, the heat flux could be reduced to 1 Btu/hour-ft^2 or less, as opposed to about 3000 Btu/hour-ft^2 for uninsulated line. Such fabrication would be worthwhile if only LH$_2$ were to be used. If LF$_2$ were circulated for an extended period, it would be more efficient to circulate LN$_2$ through the jacket, which could be done with certain types of jacketing arrangements. It would not be possible, however, with added insulation in the jacket. It was therefore concluded to use vacuum jacketing throughout the system, thus providing good properties of insulation with high flexibility of use at moderate cost. This construction would be most efficient with regard to time, in that cooldown would be reduced to a minimum, requiring only minutes as opposed to hours or days if laminar insulation or evacuated powder insulation were used.

5. Pipe Sizing

The test system is designed to operate under dynamic conditions with flow rates in the normal handling range. The test loop is designed to circulate propellant at any rate between 5 and 150 gpm. The propellant velocity is limited at the upper extreme by pressure drop through the system, which must be consistent with pump capability and permissible heat generation. The lower velocity limit must be sufficiently high to maintain any solids in an entrained state. It is further desired that a velocity be attained that will provide free turbulence for these solids for purposes of study.

The required maximum velocity is a function of the particle size and the density of the suspended contaminant, as well as of the fluid density and viscosity. Useful correlations have been summarized by Boven (Ref. 1),[*] who considers the standard velocity to be that above which homogeneous flow occurs with all particles uniformly dispersed through the liquid. According to Spells (Ref. 1), the standard velocity is related to the system characteristics as follows:

$$\frac{\rho_l \, V^2}{\rho_e \, g_c \, \zeta} = 0.0741 \left(\frac{D \, V \, \rho_m}{\mu_l} \right)^{0.775}$$

where ρ_l is the liquid density; ρ_e, the effective density [solid density $(\rho_s) - \rho_l$]; ρ_m, the mean density of the slurry; ζ, the mean particle diameter; and μ_l, the viscosity of the suspending medium. This relationship applies to particles between 50 and 500 microns in diameter.

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[*] Reference numbers apply to the List of References following the text (and preceding the Bibliography of pertinent works).

The following equation was developed by Cairns (Ref. 1) for smaller-diameter particles (from 15 to 30 microns), with a solid density of 2.7 to 19.0 g/cc and at weight concentrations of 5 to 15%:

$$V_m = 1.9 \ D^{0.2} \left(\frac{\rho_e}{\rho_1} \right)^{0.3}$$

This equation presents the velocity at which a moving bed is formed as velocity increases, and the velocity will therefore be lower than that of Spells. The data used in the development of these two equations are reported by Bowen to be at variance, but the correlations give a range of velocities for expected laminar particle motion and turbulent suspension.

Although high propellant-line velocities are desired, it is also necessary to limit the pressure drop through the system. Using Reynolds' correlation, it was determined that 2-1/2-in.-dia tubing would not produce resistance in excess of 50 psi for flows up to 150 gpm. The actual resistance would vary from 19.2 psi for B_5H_9 to 48.8 psi for ClF_3. These flows would produce Reynolds numbers in the turbulent range for all propellants at a maximum line velocity of 11.33 ft/sec. As indicated in Table 1 complete particle turbulence should be obtained at velocities less than the maximum for all propellants except B_5H_9 when iron oxide is the contaminant. Only slight deviation from turbulence is expected with B_5H_9. Other specified contaminants are of lower density and will therefore be suspended at lower velocities.

It is unlikely that empirical correlations of the above type have ever been obtained for the liquids of interest. The proposed installation will provide facilities that could be used for substantiation of these equations in the course of normal use and without adaptation. This is only one example of the basic investigations possible with the system.

Liquid hydrogen presents a peculiar situation in that even with 1-1/4-in.-dia tubing the maximum velocity will be 49 ft/sec at a pressure drop of 34.5 psia. Spells' equation indicates a required velocity of more than 90 ft/sec to provide suspension of iron oxide particles 100 microns in diameter; this would cause a flow resistance greater than 100 psi and consequent development of frictional heat. This high pressure drop is not practical with the type of pump required, and a compromise is therefore suggested in which 1-1/4-in.-dia tubing will be used. Experimental data of Spieth, et al. indicate a deviation of about 30% for the pipe friction of LH_2 in a vacuum-jacketed line as opposed to the theoretical values determined by the Fanning relationship (Ref. 2). Thus, the calculated 34.5 psi may be somewhat low and, rather than reduce the pipe diameter, the safety factor obtained by using a 1-1/4-in.-dia tube should be retained.

The sizing of the sampling branches was based on a maximum flow of 2 gpm to provide isokinetic takeoffs from the main loop under 150-gpm conditions. This results in a 0.2685-in.-dia nozzle, indicating 3/8-in.-dia tubing for the branch to retain a comparable velocity. Most of the equipment needed is available as 5/8-in. standard size.

6. Vessel Selection

Vessels with a liquid capacity of 200 gal are required to supply and receive an adequate volume for flow tests. If one vessel is to be used interchangeably for all propellants, it must be of double-walled construction at the minimum and will more appropriately be triple-walled to provide acceptably low cryogenic-vapor losses and to permit adequate control of pressure. * Each of the two tanks should have an actual capacity of about 300 gal to provide for liquid expansion, vapor-volume ullage, and clearance for entry nozzles and vent connections. Liquid fluorine can be advantageously processed in a three-wall vessel, utilizing the second shell for LN_2, as previously noted for piping. Three-wall tanks are relatively costly to fabricate, but it was concluded that a three-wall tank (such as that shown in Figure 3) was the most practical after the versatility required was considered.

An elevated vessel is suggested and will require access stairways and service platforms as shown in Figure 1. Vacuum equipment will necessarily be located as close as possible to the tanks to reduce impedance. All the relief lines are to be vented to a waste-disposal facility. Vessel support may be either at the ground level, by structurally separate columns, or at the upper service-platform level, by integral beam support. The latter is preferred, because there will be less moment on the vessel weighing system due to wind load.

B. MATERIALS OF CONSTRUCTION

1. Metals

Considerable data are available on the compatibility of the more common metals with most propellants, and sources of information are presented in the first portion of the Bibliography. Table 2 summarizes the compatibility data. In several cases no unqualified recommendations were given, and the published conditions of use are limited. Very little has been published, for example, on the handling of N_2F_4 in the liquid phase. The recommendations made in this report are not to be considered for purposes other than the specific, presently proposed use.

The metal most nearly approaching complete compatibility with all propellants under consideration is Type 347 stainless steel. Other 300-series stainless steels are acceptable for several purposes, particularly when they will not be in contact with the flowing propellants. It is recommended that all tubing, valves, fittings, gage shields, vessels, pumps, and other devices in flowing contact be constructed of AISI Type 347 stainless steel except as otherwise specifically noted.

Whenever dissimilar materials are required, such as for valve seats or plugs, it will be necessary to supply at least two identical parts of different materials. For LF_2 use, no nonmetals are acceptable for valve seats; these seats, or replaceable plugs, must be supplied in K-Monel unless other metals are specifically approved. K-Monel cannot be used with N_2H_4 or N_2O_4. Stellite, gold, and platinum are usually considered unsuitable for some propellants because of their catalytic effect and not for reasons of corrosivity. Silver valve seats are excellent for ClF_3 but cannot be used with H_2O_2 because of the catalytic effect.

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Metals to be used in gas-phase locations or where liquid contact will be essentially static are not quite so limited. Fluorine is the only propellant with which nonmetallic components are not usable, and for purposes of seals or gaskets copper or aluminum may be used if necessary although, in all cases, it is desirable to utilize stainless steel. It must be emphasized that fluorine, particularly in liquid or two-phase conditions, will react with any metal if impurities are present to create a reaction center.

2. Seals, Gaskets, and Packing

Liquid fluorine again limits the materials usable for seals and gaskets; it is incompatible with all resinous or elastomeric materials to at least some extent. All the other propellants under consideration are compatible with Teflon, and most with Kel-F. Teflon is therefore recommended for elastomeric purposes for all propellants except LF_2. It may be used as best suited in the form of chevron rings, copper braid and Teflon rings, or spirally wound with stainless steel (Flexitallic type). All valves used in fluorine service must be equipped with either stainless-steel bellows seals or with laminated metallic braid and Teflon chevron rings. All valves for the proposed installation must therefore be sufficiently standardized to permit braided copper and Teflon to be substituted for any packing otherwise intended for use.

Gaskets should be of stainless steel whenever possible. If softer materials must be used, such as gaskets for valve seats, Type 1100 aluminum may be used for all propellants. Copper and aluminum have been successfully used for fluorine service, but sufficient data are not yet available to establish a positive compatibility for seals and gaskets.

3. Windows

The system has to be equipped with viewing ports for visual or photographic observation of propellant flow, contaminant suspension, and bubble formation. Resistance to thermal shock in operations using LH_2 is a primary factor in the choice of window materials, as is chemical resistance to the various propellants (particularly fluorine).

No manufacturer has been located who can supply an off-the-shelf casing of the configuration required. The cross-sectional area of the casing must be the same as that of the connecting piping in order to maintain the same degree of turbulence and suspension of solids. The casing should also be designed with a gradual change of shape when change is necessary to provide flat, parallel, lens surfaces. Several possible configurations have been considered and, after consultation with vendors, it is believed that suitable housings could be investment-cast in Type 347 stainless steel for approximately $500 each.

Calcium fluoride, quartz, and other materials are reviewed in Section IV,U, below.

C.   COMPONENT EVALUATION

1.   Pumps

The system must circulate 5 to 150 gpm of all propellants through the test loop. The hazardous nature of the liquids limits the type of pump to those with no leakage and made of compatible materials. Gear, piston, centrifugal, diaphragm, and screw-type pumps were considered; only the centrifugal type was retained.

Diaphragm pumps appeared to be most suited for the transfer of hazardous liquids, but none were found with a capacity approaching 150 gpm; additionally, they tend to be rather costly. The principal advantages of a diaphragm pump are that the propellant does not contact moving metal parts of the pump and that the pump is a sealed unit.

Gear pumps have been frequently used (at relatively low rates of flow) to transfer some of the propellants under consideration. They are not commonly used for rates as high as 150 gpm. Experience with the smaller units has indicated a tendency toward galling of close-tolerance components in the transfer of B_5H_9, resulting in no flow or variable flow; this type of pump was therefore dropped from consideration.

In the absence of test data, it seems likely that screw-type pumps would be subject to the same problem of galling and also could not be obtained in leakless construction of compatible materials.

Piston-type pumps are prone to leakage, and high-friction moving components would be exposed to the propellants, some of which have a tendency toward negative lubricity (as noted), thereby indicating probable mechanical difficulties in operation.

Centrifugal pumps are most adaptable to variable output and can be constructed of nearly any combination of metals desired. Recent developments in mechanical seals also provide a solution to one of their most common weaknesses, that of leakage at the shaft seal. As a result, they are generally used as transfer pumps in missile systems for the more common propellants. In 1960 Aerojet-General developed a satisfactory LF_2 pump of the centrifugal type, and others are now reported in use. Such pumps are not common, however, and special care must be used in their design and construction - particularly with regard to the materials used, the type of seals, and impeller clearances.

Chlorine trifluoride and B_5H_9 have been transferred by centrifugal pumps, but no data have been published on the results of these operations. Available data indicate that ClF_3 will cause the ignition of metals similar to the ignition by fluorine if high liquid velocities occur in the region of metal impurities, occlusions, or irregularities. The characteristics are sufficiently similar to those of fluorine to indicate successful results with a pump designed for fluorine transfer. The boiling point of $53.2^\circ F$ indicates a need for refrigerated operation or operation under pressure to prevent cavitation; facilities for this would be present in a fluorine system. Pentaborane characteristics are very different, but the required pump is similar in that close clearances must be avoided and the seals must be leakproof.

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The properties of the other propellants, except hydrogen, fall in general between those of B_5H_9 and ClF_3; hence, a pump capable of handling these two would be adequate for the balance, if compatible materials of construction are employed. Flow characteristics are also grouped between these two propellants. A pump with the required capacity of ClF_3 will have adequate capacity for the other liquids under consideration.

No experience with the pumping characteristics of N_2F_4 has been reported, and some physical properties are not available. It is assumed that this substance would be somewhat similar in character to N_2O_4 as regards liquid transfer.

The proposed pump must meet other specific requirements of the system. It must be of relatively simple construction and adaptable to rapid disassembly and cleaning. It must also be equipped with leak-tight seals, preferably consisting of three separate stainless-steel bellows with provisions for pressurization or a vacuum between two of the seals. Because a single pump can be utilized for all propellants except hydrogen, it should be vacuum-jacketed to satisfy the cryogenic-operation requirements. The preferred material of construction is Type 347 stainless steel. The Paul Chemical Company recommends an aluminum construction with hard-coat anodizing on liquid-contacting surfaces for fluorine service. This unit would be less expensive and should be considered, because the supplier has had substantial experience in the field.

Multiple-stage centrifugal pumps were eliminated from consideration, due to the relative difficulty of disassembly and because the simpler, less-expensive, single-stage pump appears capable of meeting all the requirements.

Liquid hydrogen is commonly transferred by centrifugal pumps, actually presenting better pumping characteristics than LN_2. For certain centrifugal and turbine pumps it has been found that approximately 16 times as much head is required to prevent cavitation in LN_2 pumping as for LH_2. Seal wear due to nonlubricity has also been found to be greater with nitrogen. Except for fluid leakage, hydrogen-pump performance has been found to be comparable to water pumping.

The hydrogen pump must be vacuum-jacketed for use in the system. Although uninsulated pumps are used occasionally for cryogenic hydrogen, they are generally restricted in application to high-flow-rate, short-distance transfer and are not intended for recirculation. The pump should also be of dimensions similar to those of the general-purpose propellant-transfer pump to facilitate the exchange of pumps.

Pump driver selection must include consideration of the required circulation rate (5 to 150 gpm). As previously noted, had a mixer been used in the supply tank, it would not have been practical to recirculate the propellant to the same tank because of excessive heat development and consequent liquid loss. In this case, a variable-speed drive would have been necessary over a range of about 8 to 1 to couple with a throttling ratio of 4 to 1 to provide the required flexibility. By exclusion of the mixer, the pump can conceivably operate at a constant maximum rate and only the desired quantity will be bypassed to the test loop. It will still be advantageous,

however, to use a variable drive to minimize heat development in the propellant. Under the latter conditions, a turndown ratio of 4 to 1 will be adequate; this can be obtained using a mechanical speed ranger, or (depending on the economics) a turbine drive or a variable electric drive may be used.

2. Valves

The selection of valves for the propellant-circulation system is of basic importance to safety, reliability, and effectiveness. As with pumps, the valves must be of compatible materials, relatively simple, and easy to disassemble for cleaning. The special propellant valves must also be vacuum-jacketed to provide a continuous insulating barrier for the system. They should have the least possible restriction to flow when open and a minimum of dead spaces or voids that could fill with propellant during operation and might not be drained when the system is emptied. Throttling valves are required in three sizes, and pneumatic or remotely operated shutoff valves are needed in at least four sizes. Some propellant valves can be manually operated once the system is in operation, and these must be leak-tight and essentially damage-proof while in service.

Valve construction is further restricted in that seats or plugs fabricated normally of a nonmetal, such as Teflon, must be replaceable with metal parts for some propellants. The stem seals must be positively leak-tight and of compatible materials. They should also be easily replaceable if they are subject to contamination or deterioration.

Split-body valves lend themselves to these requirements very easily but are not conveniently vacuum-jacketed. Ball valves offer the least flow resistance and can be vacuum-jacketed easily, but few that do not require a nonmetal ball seat are available. A rising ball valve supplied with a hard seat is available, but the ball socket would create a reservoir of fluid that would not be drained with the valve open. This disadvantage could be overcome by tapping and bleeding the cover, but the jacketing of the unit would then become unduly complicated.

Conventional or Y-pattern glove valves appear to be most suitable for the larger sizes. These are obtainable in the required metals and can incorporate all the necessary features for cryogenic and hazardous-chemical control. They are not usually stocked by manufacturers in sizes below 1/2 in., but can be obtained on special order without unusual delay. This type of valve can be supplied with either hard or soft seats, which in some cases require a gasket. Gaskets of this type fabricated from soft aluminum or copper have been used without reports of failure in LF_2 transfer and are therefore recommended. Stainless-steel gaskets can be provided if necessary. It is also probable that Monel gaskets could be obtained. Type 347 stainless-steel plugs and bodies with K-Monel seats will provide adequate resistance to all propellants except B_5H_9, N_2O_4, and H_2O_2. For these liquids, the K-Monel parts will be replaced with aluminum or Teflon.

Cast valves of Type 316 stainless steel have been noted to fail in fluorine service (Ref. 5), due to impurities in the castings. Other data have shown wrought valves of this metal to be suitable; cast valves performed reliably when carefully manufactured and inspected. There appears,

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therefore, to be no reason to exclude castings, provided that no impurities or surface flows are permitted in the finished valve. These cast valves will be considerably less costly than barstock valves in the larger sizes.

It has been generally found that rough areas, such as threaded surfaces, present potential points of chemical attack or impurity accumulation. All surfaces subject to exposure to liquid propellant should be free of threads, and all welds used instead of threads should be ground and polished; this applies particularly to the method of connecting the valve plug to the stem.

Stem seals can be of two types, as previously noted. The bellows seal provides a more-positive leak-tightness than does the packed stem. Bellows seals are subject to failure due to "squirm" or distorted crushing of the bellows when it is working against high internal pressures or when a long bellows is required. This failure has occurred on pneumatically operated valves when both fast response and high closing pressures were present. It is not considered to be a common occurrence, however, and this type of seal is considered suitable. The alternative is a double packed seal using a long stem. The packing must be similar to that used for pumps - braided copper and Teflon for fluorine service, and Teflon chevron packing for other propellants.

Small valves (less than 1/2 in.) may be of the needle, packless-diaphragm, or globe type. The latter two are not easily available in vacuum-jacketed form, however, and needle valves may need special modification for compatibility with LF_2 and ClF_3. Small valves may be used with AN tube connections, but internal threads are not permissible.

Gate or ball-type valves are not generally recommended because of the attendant sealing problems and possible leakage. Exceptions are the high-vacuum gate valves, which would not be used for liquid contact, and possibly some ball valves of special design for cryogenic use.

Relief valves will be installed downstream of rupture disks for the inner vessels. The in-line type of valve will be adequate for this purpose, using Type 304 stainless steel with Teflon seals. Only in the event of excessive pressure resulting in rupture will these valves be exposed to the propellant (and then only to the gas phase). Teflon will be suitable for these conditions. The relief-valve cracking pressure will be set at 65% of the rupture-disk rating to maintain a safe pressure. By using self-closing valves, the entire tank contents will not vent upon disk failure. The relief valves will vent to a disposal line.

Burst disks will be required also in each section of propellant piping that can be isolated by valves. Monel disks have been used for fluorine service. However, stainless-steel disks are recommended to provide more general compatibility for this system.

3.   Piping

The need for occasional system disassembly and the selection of vacuum-jacketed transfer pipe limit the means of assembly. Normally, all-welded piping would be indicated for systems designed for hazardous materials;

this would also be desirable in a vacuum-jacketed assembly. To provide access for cleaning, however, disconnects must be included at each valve, instrument, or other mechanical device; they should be structurally strong, because the propellant piping will be subject to flexural stresses both from the weight of connected fittings and accessories, and from the expansion and contraction effects of temperature change. The connections must be vacuum-tight to 10^{-4} mm Hg and pressure-tight to 215 psia. It must be possible to disassemble and reassemble the system rapidly and with minimum realignment effort. The overall dimensions of the joints should be at a minimum to avoid a need for large-diameter jacketing. The joints must provide essentially no void areas where propellants or other liquid might be trapped when the system is drained. They should be of materials, and have a bulk, that will provide a minimum heat reservoir or radiation surface for use with cryogenic liquids.

Bayonet couplings are commonly used for LH_2 transfer and meet most of the requirements discussed above. The two significant features that reduce their applicability to the present installation are (a) that they control leakage by using nonmetal gaskets or seals, and (b) that the vacuum jacket becomes discontinuous at the coupling. Teflon seals would need to be replaced each time the system propellant is changed, which requires some additional time for reassembly. A more serious problem is the possibility of leakage through these fittings. Liquid-nitrogen leakage has been found to be more significant than is the case with LH_2; effects of other propellants in the cryogenic range have not been reported but would be a function of density and viscosity. There is also a direct metal connection between the inner and outer walls, allowing a small amount of heat leakage.

Each section of piping between bayonet couplings has, in effect, an isolated vacuum jacket. For the proposed system it is desired to retain the capability of circulating a refrigerant in the jacket for some purposes. This could be done with the isolated sections but would entail some additional circuiting that would tend to nullify the quick-coupling advantage of the bayonet fittings.

Another single-joint connection using a labyrinth seal was evaluated. This connection is similar to the bayonet type in that the inner pipe is compression-sealed by the outer pipe coupling, which consists of a V-type band. A liquid seal is maintained by an elaborate fluid path with multiple mating faces at the joint. This connection appears to be very useful for nontoxic liquids, but would tend to hold up a relatively large volume of liquid. Because this volume would be released upon disassembly, this joint was not considered further.

The dismantling of a system constructed with bayonet couplings usually requires the disassembly of sections in a fixed order because of pipe overlap. To remove individual sections of the system, special flanged sections would be required at frequent intervals. The Cryogenic Engineering Laboratory of the National Bureau of Standards (NBS) has developed a double bayonet fitting that will permit sections to be removed with even less axial movement of the line than required for the labyrinth coupling (Ref. 4). This also would require vacuum-jacket jumpers, however, and would tend to cause small quantities of propellant to accumulate in the coupling annuli.

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A coupling arrangement that meets all the requirements given, with the possible exception of high flexural strength, utilizes male and female flanges, a metallic gasket, and a V-shaped retaining coupling. This unit can be supplied in a lightweight form requiring only one bolt on each of the inner and outer couplings, or in a heavy-duty type using two or more bolts per coupling. The required axial movement is small, although more than for the NBS double bayonet. Its basic advantage is that the inner coupling is completely separate from the outer jacket, thus providing (a) a continuous jacket, (b) no metal contact of cold with warm walls, and (c) no pockets for the accumulation of propellant or contaminants. These units have been tested under a high vacuum with satisfactory results and have been commonly used for medium-pressure transfer systems. Data are available that show a heat flux as low as 8.48 Btu/ft/hour for radiation-shielded 3-in. pipe in a 5-1/2-in. jacket with LN_2. Unshielded lines produced a heat gain of 18.38 Btu/ft/hour. The fittings are available in the required size ranges and in Type 347 stainless steel; they cost somewhat less than standard bayonet fittings. The Conoseal V-shaped coupling is recommended for the proposed installation.

All propellant piping should be of Type 347 stainless-steel tubing. Vacuum jacketing of Type 304 stainless steel will be adequate, because propellant will not normally be in contact with the jacket. Type 347 was selected because of its increased resistivity to intergranular corrosion when fabricated in forms that cannot be conveniently annealed after heating above 650°F. Welded tubing falls into this classification, as will any welded vessels. This absence of annealing requirements does not eliminate the need for the stress relieving of pressure vessels to meet ASME code standards. Considering that high temperatures will not be encountered in this system, any unwelded segments may be fabricated of Type 304 stainless steel if they have been annealed after fabrication; this also applies to steel gaskets, seals, valve stems, and other small components.

No lubricants or sealants are permissible in the piping system.

Liquid-nitrogen and gaseous purge lines will be constructed of Type 304 stainless-steel tubing with welded, flanged, or AN connections. The possibility that accumulated contaminants might be carried into the propellant system from these service lines would exist if carbon steel or threaded fittings were used.

4. Filters

Three distinct cases exist in which a filter system will be required in the propellant-test assembly. In one case it will be desired to dynamically evaluate filters submitted to the Air Force; a section of the test loop in which filters can be conveniently held is thus needed. In another case it would be perhaps the intent to investigate some phenomenon in the absence of the particulate matter normally present in the specified propellant; hence, this same test-loop section would be used in conjunction with a filter of known high efficiency. In the third case it would be necessary to place smaller filters in the analytical withdrawal system, either for evaluating the main line filter, or to avoid the possible clogging of small orifices within the analysis unit (e.g., liquid-sampling valve for a process gas chromatograph).

The large filter should be capable of handling up to 150 gpm with a minimum pressure drop. The filter could be fabricated from austenitic stainless steel with welded construction, and with Teflon or soft-aluminum gaskets. The filter should be compact, easy to remove for cleaning, and vacuum-jacketed to prevent heat leakage. Sintered stainless powder filters cannot be recommended for all propellants. Possibly microweave 304 stainless-steel mesh when suitably passivated, can be used for limited times with all propellants. These microweave elements are available in size ratings to 10 microns. The small filters could be constructed of similar materials and should be sized for a maximum flow rate of 3 gpm with a pressure drop (clean) of about 2 psi. The elements should provide the best possible solids removal to permit checking of the efficiency of the large filter.

Both wire-mesh and sintered filter elements are known to slough off facing material to some degree. For the proposed test circuit this deterioration during use must be kept to an absolute minimum to provide accurate analytical results and to ensure the proper operation of system components. Because the elements will be cleaned and examined between test runs and because the runs will be of relatively short duration, this erosion is not likely to be serious.

A third type of element, described as porous-metal-faced, is reported to perform with substantially better physical integrity than the normal sintered powder facings. This unit can be supplied in compatible metals and with a nominal 5-micron rating, 20-micron absolute filtration. Filters are available with a 150-gpm capacity with pressure drops ranging from 1.5 to 15 psi with LO_2 or LN_2. Vacuum-jacketed, T-type assemblies are available from PurOLator and other manufacturers. These units, employing Monel elements, are in present use with LF_2. Although the elements can be cleaned effectively, it appears desirable not to interchange elements for various propellants but to provide separate elements for each liquid. In this case Monel elements may be used to advantage with fluorine or ClF_3, and stainless steel may be used for the other propellants.

5. Vacuum Equipment

Purging of the system prior to the introduction of propellant will require evacuation to remove all traces of air or gas that would affect the propellant. This method will also provide an accurate leak check before a run is started. Periodic pumpdown of jacketed lines will be required, and the supply-vessel shells will be evacuated for some runs. Simultaneous evaluation of these three areas will not normally be required, and pumping facilities may be sized for only the greatest demand of one area.

A moderately high vacuum, about 10^{-4} torr, is needed in each area; this will require a mechanical roughing pump to reduce the pressure to about 10^{-1} torr and a diffusion pump to produce the ultimate pressure. The use of a Roots type of intermediate blower was investigated and found unnecessary for the pumping-rate requirements. Turbomolecular pumps, ion pumps, and ejectors were considered and rejected as unnecessary or economical under the probable operating conditions.

An oil diffusion pump must be equipped with a backstream cold baffle to prevent the migration of oil vapor into the system. It will not prevent propellant vapors from contacting the pump oil, however, and other means (such as a cold trap) must be used for this purpose. Pump oils are available for use with LO_2, and different oils may be used with nitrogen and hydrogen. None of these oils is known to be suitable for use with fluorine or ClF_3, however, and absorption of other fuels in the pump oil would introduce hazardous mixtures. For these reasons it was concluded that the system should not be evacuated before flushing and purging. In effect, the vacuum pumps will be required to pump only air, nitrogen, or an inert gas. The use of a cold trap was investigated for the condensation of vapors preceding the pump. Calculations indicate that at a temperature of $-320°F$ (LN_2 trap) the concentration of fluorine vapor at the pump would be excessive. A trap using liquid helium could be employed, but such a device would be expensive to use and maintain.

The size of the vacuum equipment is based upon approaching a pumping rate of 1500 liters/sec to 4×10^{-4} torr. To provide this rate at the propellant tank, an unpractically large connection would be required for this size of tank. Using the methods described by Guthrie and Wakerling (Ref. 5), a tank connection of 4-in. diameter was determined to allow a pumpdown time of about 10 min. The limiting rate will be that required for the piping system. Based upon 2-1/2-in. lines, this time is determined to be less than 10 min. However, this value will be affected by the number of valves or other impedances in the system and is subject to a large factor of uncertainty for a long, irregular line. A 10-in. diffusion pump with a rated capacity of 4100 liters/sec will permit simultaneous evacuation of both propellant tanks with a reasonable pumpdown time.

The evacuation of pipeline jackets will be a somewhat slower process but is only occasionally necessary and can be accomplished before the internal system as a whole is ready for evacuation. Calculations indicate that the pumpdown time required for this phase of startup would be less than 1 hour. Irregularities in the piping interior affect the rate substantially, however, and a large margin of safety is desirable. A vacuum of 4×10^{-4} torr in the jacket will provide an efficient thermal barrier for the requirements of this system, without necessitating elaborate piping or equipment limitations.

Outgassing from piping walls, gaskets, and internal sources may be kept to a minimum by preliminary treatment such as thorough heating of the system; this should be done particularly on initial operation of the system and each time the system is subsequently placed in use. If time is not a critical concern, the repetitive heating may be eliminated by providing a longer pumpdown time. Considering that a high vacuum will not have to be maintained for long durations and that cryogenic liquids will be charged after evacuation, further reducing the pressure in the jackets, outgassing is not likely to present a serious problem.

The valves selected for use throughout the propellant system will be vacuum-tight. Special high-vacuum valves will be required in the vicinity of the diffusion pumps - in particular, an angle valve at the pump and gate valves at the various system-component-isolation points. These valves are available as standard items from several manufacturers of vacuum equipment.

6.   Isokinetic Sampling

A requirement of the system is that representative samples be taken from the main propellant-circulating stream for analysis in the side branches. As previously noted, a 0.2685-in.-dia nozzle will provide constant velocity sampling at 150-gpm rates to provide a branch flow of 2 gpm.

An isokinetic sampling device of the required configuration is not available as an off-the-shelf item but can be readily fabricated; a suggested design is show∟n Figure 4. It is apparent that, to provide an orifice velocity equal to the main-line velocity, the volume withdrawn to the side stream will have to vary in proportion to the actual main-line flow rate when the rate is less than the maximum. A pressure-balancing method of equating velocities is described in an Air Force report (Ref. 6) on sampling techniques, which simplifies the flow adjustments for normal fluids such as RP-1. This method is not applicable to cryogenic fluids or to highly reactive liquids, however, and recourse must be taken to actual flow measurement in each line with a resultant manual adjustment of flow rate in the sampling line; this would require only a chart calibration of main-line flow vs branch flow for constant velocity, for an otherwise fixed system.

For maximum accuracy, the sampling nozzle could be attached to the propellant pipe by a bellows connection, thereby permitting adjustment of the nozzle across the propellant stream with a screw-type positioning rod attached to the pipe through an eye welded to the external surface of the nozzle. The desired accuracy will be obtained with a fixed-position probe under turbulent-flow conditions but will deviate as laminar flow begins. This deviation can be compensated for by means of a mechanical mixing vane ahead of the probe. The adjustable probe would be considerably more difficult to fabricate, and it is not believed that the contaminant-concentration gradient across the stream would warrant such a modification unless the test branch were to be used specifically to measure this gradient.

The 2-1/2-in. propellant line would be on the same level as the sampling branch, and the connections would be straight tubing. The 1-1/4-in. hydrogen line would be elevated a few inches and would require either bent-tube connections or flexible tubing, the former being preferred to prevent hydrogen hold-up in the line.

D.   INSTRUMENTATION

1.   Temperature Indication

It will be desirable to indicate and/or record the fluid temperature in each of the propellant tanks and in two or more places in the test loop. Although temperature can be measured in many ways (glass thermometers, dial thermometers, bimetallic strips, gas thermometers, thermocouples, resistance thermometers, etc.), no one instrument can be conveniently used to cover the range from -423 to +200°F. Copper-constantan thermocouples can be used satisfactorily for the temperature range from +200 to -325°F. A single-range, high-precision indicator or recorder should be suitable for use with as many thermocouples as are needed. Thermocouples are relatively inexpensive, have a rapid temperature response, and can be obtained in small

sizes (1/8 in. OD or less, including protective sheath) for installation in small lines and equipment; they are not easily broken and retain their calibration for long periods.

The gold-cobalt vs copper thermocouple has been used for temperature measurements at -423°F (LH_2), and its range may be extended to $+200^\circ$F. As compared with copper-constantan at 60°F, it produces a little less than one-half the electro-motive force per degree Fahrenheit at LH_2 temperatures. The output vs temperature curve is not linear. Wires are subject to heat leakage and to lack of homogeneity. By using carefully caligrated thermocouples and a three-range thermocouple pyrometer, it is probable that an accuracy of $\pm1^\circ$F can be obtained over the range from -423 to $+200^\circ$F.

If errors of 0.5°F or less are required, calibrated resistance thermometers should be used for measurement in the LH_2 temperature range. Thermocouple measurements could then be used for LN_2 and higher temperatures. The sensing elements of either system can be adapted to fit the same pipe or tank connections.

2. Pressure Measurement

Pressure throughout the system is of critical importance. Safety valves and burst disks will be individually selected for desired pressures. After the measurement of pressure, normal venting may be effected manually or automatically. Visual gages will be desirable at several points. Standard Bourdon tubes utilizing stainless-steel sensing elements will be suitable for this purpose, although pre-cleaning and passivation will present mechanical problems. These operations may be accomplished by drilling a hole in the sealed end of the tube, flushing through the required cleaning and passivating solutions, and then welding the end closed.

Recorded pressures or the pressures used for control will require transducers of the standard type constructed of stainless steel. Diaphragms that are properly cleaned and dried, and are of high quality, will perform without malfunction. It must be considered that very thin diaphragms do not require much contamination-caused reaction to reach ignition temperatures with LF_2.

3. Flow Measurement

A large number of devices available for flow-rate indication were studied with the purpose of selecting the best instrument or instruments to indicate and/or record the propellant flow rate in the proposed test loop. Seven different types of instruments are described in Table 3.

All but the simplest and most rugged instruments are ruled out by the stringent requirement for corrosion resistance and the need to withstand repeated cleanings and passivation. The positive-displacement meters and the recently developed mass-flow meters with numerous bearings and parts seem too complicated to be practical for the repeated cleanings required. The need for a single instrument to indicate the extremely wide range of flows (from 5 to 150 gpm, or a 30-to-1 ratio) rules out orifices and Venturi

meters that normally operate over only a 4-to-1 ratio. A Daniel orifice
flange that permits the use of several sizes of orifice plates without
shutting down the line would be too bulky for use with cryogenic fluids.

Rotameters can normally be used over extremely wide flow
ratios, but rotameters with glass tubes could not be used in the case of
fluorine and ClF_3. Rotameters with metallic tubes may be used, but with
reduced accuracy. Rotameters would be difficult to adapt for use with cryo-
genic fluids, because a small amount of vaporization in the tube would make
accurate flow measurements extremely difficult.

A relatively new flow-measurement technique utilizes the
addition of a known quantity of radioactive material to the stream being
measured. The concentration of radioactive material is then measured by a
radiation counter so that the active stream flow can be computed. This metho.
is expensive and complicated and would be extremely difficult wherever many
different kinds of propellants are used. The use of a recycling system would
further complicate the radiation-count method.

The turbine or vane type of flow meters, well known in the
rocket industry, seem to be ideally suited to the present requirements. They
are relatively simple, accurate, and usable over wide flow ranges. Flow rates
can be recorded with an oscillograph, or a frequency converter can be used to
give a visual indication of flow rate. These meters are available in Type
347 stainless steel, have been used with cryogenic liquids, and are currently
being tested with LH_2.

An ultrasonic instrument is manufactured by Gulton Indus-
tries, Inc. that transmits an ultrasonic beam through the pipe; a set of
receiver-transducers on the opposite side of the pipe indicate the direction
and magnitude of flow. There is no pressure drop in the pipe or connection
to the pipe. A claim has been made for 1 to 2% accuracy for pipe having
diameters from 2 to 18 in. This instrument would probably work well for all
except the cryogenic fluids; vacuum jacketing would probably considerably
reduce the sensitivity.

Another type of device, manufactured by the Ramapo Instru-
ment Company, utilizes the dynamic forces acting on a body fixed in the center
of the pipe to actuate strain gages in a bridge circuit outside the fluid
stream. The electrical output is proportional to the square of the flow rate.
Accuracy to within ±1.0% is claimed. This instrument would have to be cali-
brated for each propellant and is not nearly as accurate as the recommended
turbine-type meters.

Several improved mass-type flow meters have been reviewed.
In each case they appear to be too complicated or too difficult to make com-
patible with all the specified propellants.

4.   Liquid-Level Measurement

         A great number of liquid-level indicators have been studied
with the aim of selecting the best instrument or instruments to indicate and/or
record the liquid level in the propellant tanks. Instruments based on at least
seven different principles of operation were studied (Table 4).

         Due to the wide range of liquid densities, the various types
of corrosion problems, and the cryogenic temperatures, it does not seem
practical to use gage glasses, outside tubes, or internal-float devices to
measure the liquid level. This leaves for consideration the devices that can
be attached directly to or inserted in the tank.

         Because the liquid in the tank will have to be in a high
state of agitation in order to keep the solids suspended, float-type level
indicators would not function properly. Instruments that depend on varying
conductance or capacitance at a probe in the tank would be at a disadvantage
because they would probably have to be calibrated for each different liquid
used. Instruments that depend on X-rays or gamma radiation between a movable
(or fixed) source and a receiver would be at a distinct disadvantage when used
with a large multiwalled tank. This leaves three types of liquid-level measure-
ments, each of which would depend upon the known density of the liquid being
measured. They are described below.

         a.   Direct-Weight Instruments

         The tank and equipment are mounted on a large platform
scale. Piping and process lines do not interfere with the weight measurements.
The Toledo Scales Corporation makes a scale accurate to ± 1 lb in 10,000 lb.
This would correspond to $\pm 0.7\%$ of 200 gal of LH_2, or $\pm 0.03\%$ of a tank of ClF_3.

         b.   Differential-Pressure Instruments

         A differential-pressure transmitter is connected to
the top and bottom of the tank by small-diameter tubing. Differential-pressure
transmitters are available (from the Foxboro Instrument Company) that read to
as low as 0 to 5 in. of water differential with an accuracy of $\pm 0.5\%$ of full
range; this corresponds to approximately ± 0.4 in. of LH_2. A less sensitive
instrument would have to be used with the more dense liquids (0 to 50 or 0 to
100 in. of water differential). These instruments are available in corros_on-
resistance cases (stainless steel, Monel, etc.) with Teflon gaskets and with
either pneumatic or electronic transmitters.

         c.   Gas-Bubbler Instrument

         This type of liquid-level indicator measures the
pressure required to force a gas through a dip tube in the tank of liquid.
Essentially it measures the height of liquid through which the gas is bubbled.
The accuracy is at least as great as that of the differential-pressure-trans-
mitter instruments. However, there is the disadvantage that a small volume
of gas is continuously forced r..to the system.

Olsen of NASA, in a thorough study of mass and level gages for LH_2 tanks (Ref. 7), concluded that the devices best suited for propellant utilization were (a) pressure-head-manometer systems, (b) capacitance systems, (c) "hot" wire systems, and (d) ultrasonic switch-point sensor systems. For filling, the hot-wire point sensor was reported to be the most satisfactory, followed by weighing and floats. In the test system under consideration, many propellants would have to be gaged by the same device, and LH_2 would be the most difficult to gage. Because many different propellants will be used, it would save much time and labor to employ a level-sensing device that does not require calibration for each propellant. A very bulky float would be required for LH_2, making it impractical in the tanks with recycling and agitation. Thus, weighing and a pressure-head manometer appear to offer the most practical approaches for the proposed test systems.

Electronic load cells may be used for direct weighing instead of conventional scales, because they have faster response and higher sensitivity and require less maintenance. A quotation on this system was received that guaranteed a weighing accuracy of +2 lb with a tare weight of 4000 lb and a net weight up to 5000 lb. Such installations are subject to temperature and wind effects to a relatively high degree. The limitations imposed by connected piping are significant but will be partially compensated for by the use of bellows connections. The unit described was equipped with a weight indicator and recorder that could be located up to 250 ft from the load point.

The direct-weight liquid-level control utilizing load cells is recommended for the proposed system.

5. Vacuum Gages

Heat flux in the high-vacuum range is closely related to the degree of vacuum attained. Assurance of the complete elimination of volatile fluids in the propellant system also requires knowledge of the system pressure. A vacuum to 0.1 torr can be measured adequately by instruments of the diaphragm or bellows type. Lower pressures require more complex devices, such as the thermocouple gage, which is accurate to about 10^{-3} torr. For the measurement of working pressures in the proposed system, it will also be necessary to use an ionization gage that will cover a range from 10^{-3} to 10^{-7} torr.

Combination gages, including both the thermocouple and ionization gage, are available from several manufacturers, and up to six leads can be incorporated in one instrument cabinet. Depending precisely on the number of discontinuous vacuum systems in the proposed assembly, one of these instruments may adequately provide vacuum measurements without a need for disconnecting leads, thereby permitting a continuous check of system components.

E.   PROPELLANT AND VENT-GAS DISPOSAL

1.   Safety Considerations

All the propellants under consideration for use in the proposed system are hazardous chemicals. Most are extremely toxic, and all are capable of causing fires or explosions if improperly handled. Extensive information has been published on the handling of these materials, and operators must be familiar with toxicity and ignition characteristics. Manuals that include handling information for some of the propellants are listed in the Bibliography.

The prime criteria of safety with this system are cleanliness, leak-tightness, and compatibility of materials. Any foreign materials in the system, particularly of an organic nature, are potential sources of system failure. With some propellants, the presence of air or water in minute quantities will cause failure. Fluorine in particular is capable of reacting with any material if a reaction is started that generates enough heat to raise the associated material to its kindling temperature.

2.   Fire or Spill Control

Supply tanks and other major equipment should be protected by a water-spray system that can be remotely controlled. Although some propellant fires are not extinguishable by water, the water in these instances serves to cool the equipment and to dilute and wash the propellants away to a disposal basin. The system would be in the form of a water-deluge system using alternate fog and coarse-spray nozzles. Additional high-pressure nozzles should be located under the equipment and be oriented so as to wash spilled liquids toward a flume. Depending on the location of the system, other refinements (such as a nitrogen blanket) may be desirable.

3.   Vent-Gas Disposal

Cryogenic propellants will generate appreciable volumes of boiloff vapors when they are charged to the system. Other propellants may have a vapor pressure high enough to require occasional venting, and vapors will remain in the system after the draining of any propellant. Facilities must be available for the continuous removal of cryogenic boiloff vapors, some of which may be vented directly to the atmosphere while others should be burned or scrubbed out if personnel are near the test area. In addition to the gravity-drain and the tank-venting systems, a small powered-exhaust system should be included for the venting of all likely leak sources such as pumps, control valves, and batch-sampling points. If the installation is to be in a building, a general exhaust system will be required that should probably be of the downdraft type. Leak-indicating paints, instruments, or alarms can be included with the exhaust equipment.

Disposal procedures have been established for each propellant. Because of the range of propellants under consideration, at least two vapor-disposal devices will be required. One of these can be a scrubber, such as a limestone-packed column for gases such as N_2O_4. The other will be of the fume-burner type, which should then vent to a tall stack equipped with a water

spray for the disposal of such materials as ClF_3 and B_5H_9. All vents, explosion disks, and local exhaust hoods will be directed to these control devices. The propellant system is designed with a drain valve that will permit the transfer of liquid to a tank or truck, or directly to disposal, upon completion of a test run.

F.   SYSTEM PREPARATION

1.   Decontamination

The proposed test facility is for intermittent use. Consideration must therefore be given to the problem of reactivation after use with a different propellant. Cleaning and decontamination schedules have been established for all propellants except N_2F_4 and are described in manuals dealing specifically with this subject (see Bibliography).

Upon completion of a test run, the propellant will be emptied from the system by means of a valve supplied for that purpose. Low-pressure nitrogen will be used as the displacement gas for all propellants except LO_2, which may be balanced by dry air in withdrawal. The pump-drain valves and drains on all other components will be opened, and residual fluids will be released by means of nitrogen pressure in the system. When all liquid has been emptied, the system will be continuously purged with nitrogen until indicators show that no propellant remains.

The system will then be filled with a degreasing solution, either solvent or detergent (depending on the propellant) and left standing for at least 4 hours. The solution will be drained, and the system will be rinsed with water or steam-cleaned. The final step will be to dry with nitrogen and to seal all openings until preparations are made for the next run.

Detailed instructions for these steps are given in manuals, and operating procedures should be developed directly from sources such as The Handling and Storage of Liquid Propellants, from the Office of the Director of Defense Research and Engineering. Appropriate sources are listed in the Bibliography.

2.   Reassembly of System

Two factors are of prime importance in assembly: cleanliness and leak-tightness. Both should be checked at every opportunity, because corrections become much more difficult as the system approaches complete assembly. Procedures are also established for this phase of work, emphasizing the use of clean degreased tools, lint-free clothing, and dust-tightness during assembly.

All systems should be purged with dry nitrogen following assembly. For hydrogen systems, this purge must be followed by evacuation to prevent the condensation of nitrogen when LH_2 is charged. For cryogenic-propellant runs, the system must be leak-checked under both high-vacuum and maximum-pressure conditions.

G. CONTAMINANT-ADDITION SYSTEM

1. Accepted Methods of Charging

Due to the extremely wide range in the physical characteristics of the materials to be added (solids, liquids, gases, vapors, and cryogenic liquids) and to the extremely wide range of quantities to be added (0.2 g to more than 6000 g) with high accuracy (2 to 10%), five separate contaminant-addition devices are required. Every effort has been made to simplify the equipment and to reduce the number of separate parts. As a result, all five systems use a single flange for entry into the test system, and only three separate inlet lines are required. The opening for the flange will also serve as a manhole for the cleaning of the tanks.

The five contaminant-addition systems and the reasons for their selection are discussed below.

a. Liquids

A two-feed, positive-displacement, chemical-injection pump, with a micrometer adjustment from zero to the maximum stroke, was selected as the most accurate, versatile, and reliable means of adding the contaminant liquids. Stainless-steel pump parts, with Teflon packing, will permit the injection of almost any liquid desired. The large and small pump feeds (one each), with each feed adjustable from zero to the maximum stroke, make possible accurate injection at an extremely wide flow-rate range.

b. Solids

The bomb method has been selected as the simplest and most accurate method of adding solids. The desired weight of solid will be measured into a bomb containing large ball valves at each end. The upper valve will be closed after the solid has been added, and the lower valve will be opened. The solid will then be washed into the system by a recycle stream. To facilitate the addition of the solid into the bomb, a mechanical metering device will be provided; this device will either be an accurate batch-loading chamber with variable chamber size or a small continuous feeder that can be turned on for various lengths of time. The addition of solids by slurrying with the various liquid propellants was ruled out as too difficult or too complicated for the present system.

c. Water Vapor

For the addition of water vapor, a known volume of liquid water will be vaporized in an electrically heated line and will be discharged into the propellant system. A correction will be made for the amount of water left in the line.

d. Liquid Carbon Dioxide, N_2, and Other Cryogenic Liquids

A separate method is being incorporated for the addition of cryogenic and low-boiling liquids to eliminate the difficulties of pumping, metering, and accurately measuring small quantities of liquid.

Methane, nitrogen, or other cryogenic liquids will be measured as gases from calibrated-pressure tanks (at known pressures and temperatures) and condensed into the liquid phase in a special condenser. The special condenser will consist of a pressure vessel capable of being cooled by various cryogenic liquids. Temperature may be controlled over a narrow range by adjusting the pressure on the jacket liquid. A valve at the bottom of the tank will be opened, after the desired weight of material has been condensed, and the liquid will flow into the liquid-propellant system under its own vapor pressure at a rate fixed by the temperature of the jacket liquid.

e.   Gases

Calibrated pressure vessels and precision pressure gages will be used to measure the gaseous contaminants. The temperature of the gas in the pressure vessels will be measured so that both the temperature and the supercompressibility of gases can be used in computing the quantity of gas that has been added. It is believed that this is the simplest, most versatile, and most accurate method of adding known quantities of gas into the system.

2.   Devices for Measuring Solids

The accurate measurement of very small quantities of abrasive materials by automatic or remote means presents a significant problem. Elaborate feeders are available that are capable of this type of operation, but most are rather costly and too heavy or bulky to install on the vessel's manhole flange. Two low-priced instruments that appear acceptable were checked for reproducibility.

A micro-setting powder measurer was received from the Santa Anita Engineering Company and was tested for consistency of delivery at five different settings. The tests were made with commercial-grade sandblast sand (silica) that had been screened through a 60-mesh Tyler screen (250 microns and smaller). Nine separate readings (volumetric displacements) were taken at each of the five settings, with the following results:

Setting	Average Weight Delivered, g	Maximum Deviation, g	Deviation, %
1	0.225	-0.005, +0.005	2.2
2	0.687	-0.006, +0.005	1.7
3	2.32	-0.04, + 0.03	1.7
4	3.45	-0.02, +0.01	0.6
5	9.12	-0.11, +0.15	1.6

The powder measurer was found to be of approximately the right size to deliver 10 to 50 mg of solids per gallon to a 200-gal tank. The measuring accuracy ($\pm 2\%$) was nearly constant throughout the size range; hence, the $\pm 6\%$ overall accuracy should be easily obtained.

Another constant-feed device is manufactured by the Syntron Company. A small unit was obtained for laboratory measurement of reproducibility. Using fine iron oxide powder, results were obtained within $\pm 2\%$ at a given setting for rates near the maximum required. In the minimum-rate range, the results indicated reproducibility within $\pm 5\%$. Certain modifications

would be necessary before this device could be used. For example, it should be equipped with an air motor rather than the standard electric drive; it would also require reconfiguration of the product-discharge area. The manufacturer reported that he can make these changes at little additional cost.

3. Rejected Methods of Charging

a. Slurries

A method of introducing solids in the form of a suspension in the test fuel was considered. In this system, the solids to be charged would be weighed and placed in a cylinder equipped with an agitator. Liquid would then be added and mixed with the solids, and the entire contents of the cylinder would be discharged under pressure to the main storage vessel. An alternative method would be to prepare a slurry of known concentration in a batch tank held at a constant temperature. The solids, kept in suspension by continuous recycling through a pump, would be charged to the system by means of a three-way solenoid valve used to divert flow from the recycle line. Control of the quantity charged to the test system could be by direct metering through an integrating recorder or by automatic timing based on pump-flow calibration. The charging line would be purged with inert gas or recycled fluid from the test system to ensure complete addition of all the contaminant.

The principal advantage of the latter method is that a new batch of contaminant would not have to be prepared for each test. The concentration of contaminant in the test system would be adjustable by direct metering of a suspension in a steady-state condition. Temperature effects on the test system would be consistent, and a minimum amount of pressurizing gas would be needed, if any.

However, this method of introduction includes all the handling problems of the large test system and, in some cases, magnifies them. For example, no pump is available that can be used for all the propellants. For the introduction system a broader capacity range is required; this makes the selection of a suitable pump even more difficult. Even when a constant-temperature bath or some other heat-balancing method is used, it may still be difficult to accurately make up the cryogenic-vapor losses. This makeup would be required in order to maintain a constant contaminant concentration. It is questionable whether heavy contaminants such as iron oxide could be maintained in a uniform suspension in LH_2. The slurry method appears to be impractical, although it could possible be utilized in a simpler system.

b. Solids or Liquids

A method was considered for charging either solids or liquids volumetrically from a reservoir located directly above the propellant-mixing tank. The reservoir would be closed at the bottom with a ball-type valve fitted with one or more calibrated recesses. The valve could be drilled to allow an inert gas to eject the contents of the cup when the valve is turned, thereby causing a positive introduction into the mixing tank. This system is routinely used for small-scale measurements and provides accurate, reproducible results. It is limited, however, to a total charge consisting of multiples of the calibrated cup volume, and the total could not be easily changed.

c. Gases

Direct metering is a logical alternative for the addition of gases, the basic problem being that of accuracy in the low range. The method of charging from a cylinder at known pressure and temperature conditions, with control of the charge by the change of conditions, appears to be the most reliable and practical.

H. TEST-SYSTEM CONSTRUCTION

The system, as developed, includes relatively few vessels and major equipment items; although it is not unduly complex as compared with present-day missile-test equipment, its cost cannot be directly compared with that of a facility such as a small chemical plant.

The recommended installation consists of a two-deck steel structure, 20 ft wide by 35 ft long, supporting the vessels, vacuum equipment, heat exchanger, and contaminant-addition equipment. The test loop will extend some 25 ft from the center line of the vessel and will be at a convenient working height over a smooth-finish, chemically resistant, concrete pad. Concrete flumes will extend from the pad to liquid-spill disposal areas.

Options could be taken in the design of the prototype - such as the use of two-wall tanks, minimizing waste-disposal facilities, and reducing instrumentation - to reduce the overall system cost by approximately 25%. These economies would not affect the reliability of the system and would limit the functional capacity only slightly.

IV.   STUDIES OF ANALYTICAL INSTRUMENTATION

Information was compiled on the availability of a variety of on-stream analyzers. Instruments of a given type are compared in tables associated with brief descriptions of operating principles. The chief source of information was manufacturer specification sheets, which were supplemented by information derived in personal and letter contacts. Though extensive, the information is not complete in all cases and the survey should not be considered exhaustive. (Dashed spaces appearing in the tables indicate that information was not available.)

Texts are available on process instrumentation and should be consulted for further reading. Three particularly thorough books (see Bibliography) are D. M. Considine's Process Instruments and Controls Handbook, W. G. Holzbock's Instruments for Measurement and Control, and S. Siggia's Continuous Analysis of Chemical Process Systems. Other sources listed in the Bibliography contain, for the most part, descriptions of process instruments or applications of instruments to on-stream analysis. Addresses of manufacturers are presented in Table 30, and specific techniques and instruments are described below.

A.   ACTIVATION ANALYSES

Many of the elements may be activated by irradiation with elementary particles to form radioactive isotopes of the same or a new element. These isotopes subsequently decay, yielding radioactive emissions that are measured to provide qualitative and quantitative analyses of the sample. Activation may be accomplished by means of alpha particles, electrons, protons, neutrons, or photons; analytically, however, activation with neutrons is used most widely. Charged particles have difficulty penetrating the electron cloud around the atomic nucleus and therefore give rise to relatively little activation; most elements have a low cross section for photon interaction. Sample activation may be accomplished with fast neutrons (neutrons having energies about 0.5 Mev) or thermal neutrons (those having energies of about 1 to 4 ev, or less). Thermal-neutron reactions are widely utilized for the measurement of elements that have atomic numbers above 10. The reaction is an $(n, \gamma)^*$ reaction in nearly all cases, such as $Na^{23}(n, \gamma)Na^{24}$. Conveniently, the gamma emissions from various activated elements are at different energy levels; thus, it is possible to determine several elements in a sample.

Many of the elements also undergo reactions with fast neutrons; where the reaction interferes with thermal-neutron activation analysis, provision must be made to eliminate this interference by use of the proper shielding or moderator. With the lighter elements, fast-neutron reactions occur that sometimes make possible their detection by the activation technique. Fast-neutron reactions do not always yield γ-emissions - (n,p), (n,α), or $(n,2n)$ reactions are more common in fact - although at times γ-emissions accompany the other particle emissions.

Charged particles are detected by means of ionization chambers, proportional counters, or Geiger counters; γ-emissions are measured with

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$^*(n, \gamma)$ represents neutron in, gamma (photon) out.

scintillation counters. Because of the rapid development of γ-ray spectrometers in recent years, neutron-activation analysis has developed into a sensitive and important technique.

For activation work, neutrons may be obtained from isotopic sources, electrostatic accelerators, linear accelerators, or reactors. The important properties of the four available isotopic sources are compared in Table 5, and characteristics of four neutron generators are given in Table 6. Linear accelerators and reactors are comparatively expensive, require a very large working area, and generally are not easily adapted to routine stream analysis. Linear accelerators provide neutron-flux densities of 10^9 to 10^{13} $n/cm^2/sec$ and cost from \$200,000 to \$750,000. Reactors also provide high neutron fluxes at relatively high cost. For example, the Aerojet-General Nucleonics AGN 201 reactor is being modified to yield a neutron output of 10^9 n/sec and will cost about \$125,000. The General Atomics TRIGA Mark I reactor provides a continuous neutron-flux density of about 2×10^{12} $n/cm^2/sec$, and the cost is \$180,000. The prices given here for linear accelerators and reactors generally do not include the readout and other ancillary equipment required for useful application to activation analysis.

An important and integral part of the system for neutron-activation analysis is the sample-handling facility. Assuming that a 5-gpm flow rate could be employed during activation studies, the propellant flow would be 6.1 in./sec through a 2-in.-dia pipe. Irradiation perpendicular to the line of propellant flow would result in prohibitively short exposure times. By irradiating along the axis of a 3-ft section of Z-shaped pipe, irradiation times of about 6 sec could be obtained, which would assure the adequate activation of short-lived isotopes. Some representative applications are the determination of Mn, Co, or Ni, or of other tank or filter materials in N_2O_4, N_2H_4, etc. Boron has a very high absorption cross section; consequently, impurities in B_5H_9 would be masked. Iron and silicon have low cross sections and are not determined at low levels by thermal-neutron activation. The neutron output of most sources is not monoenergetic, and in general will consist of fast and thermal neutrons. Thermal neutrons may be removed by shielding with a material having a high thermal-neutron cross section, such as cadmium; fast neutrons are slowed to thermal velocities by a moderator such as water, paraffin, or other material high in hydrogen content or in low-atomic-number elements.

The rapid flow of propellant through the sample lines also presents a problem in the measurement of γ-emissions. One method of surmounting the problem is to place a group of scintillation counters in parallel along the sample line; another is to coil the sample line around the scintillation counter; a third is to pass propellant into an enlarged pipe section to slow the flow rate for counting. In the selection of sampling lines, it is imperative that the lines be transparent to neutrons and γ-rays; conveniently, several stainless steels are transparent to both.

B.   PARTICLE SIZE

There are basically two methods for determining the size of solid particles suspended in liquids: (1) separation of particles followed by a count and measurement, and (2) continuous counting and measurement of particles as they are carried along in the flowing liquid stream. Instruments

marketed to measure particles by the former method were surveyed for the Air Force under Contract AF 04(611)-4578 by the Fluor Corporation (Ref. 8). The present discussion is limited to continuous monitors of the latter type.

Instruments for the continuous measurement of particle size are available from the Sperry Products Company, Royco Instruments, Inc., High Accuracy Products Company, and Phoenix Precision Instrument Company; the respective techniques employed are sonic, nephelometric, turbidimetric, and light scattering. The operation of each is discussed below, and the characteristics are given in Table 7. Coulter Electronics, Inc. also makes a particle counter, but the instrument is unfortunately capable of batch operation only.

1. Sperry Products Company

The Sperry liquid-contaminant-level indicator is an ultrasonic instrument employing the pulse-echo technique for detecting micron-range particles in liquids. A short-duration, 5-mc, ultrasonic pulse is projected to a focal point in the liquid stream. Particles are sized by measuring the energy they reflect back to the transducer as they pass through the ultrasonic beam. Reflected signals are amplified and passed on to a multiple-gating system. The gated area corresponds to a predetermined distance in the liquid. Any signal from the gated area that exceeds a preset level causes the gate circuitry to register a pulse on an electronic counter. The total count registered is proportional to the number of particles exceeding a preset size in the specific volume of fluid in a given time. The three-deck instrument provides four gates for the simultaneous counting of particles in four micron ranges.

The instrument was originally designed for the oil and gas industry. Of the four devices compared, the Sperry unit is most nearly a process instrument. The sample lines may be of stainless steel or other compatible material, but a small quartz, lithium sulfate, or barium titanate transducer must be placed in the liquid stream and be held with an epoxy adhesive or other cement. The sample must be chemically compatible with the transducer and must not alter the sensitivity, as cryogenic fluids are apt to do. The instrument is limited by the lower particle-size capability of 25 microns. The liquid-contaminant-level indicator is not a quantity product or an off-the-shelf item, but rather is assembled from components upon receipt of an order.

2. Royco Instruments, Inc.

The Royco Model 300 liquid-borne particle monitor is based on nephelometry (involving the scattering of light by solid particles). The flowing stream is illuminated through a 1 by 2-mm slit by light of a fixed wavelength. Entrained solids (or liquids or gases) having a refractive index different from the suspending medium reflect an amount of light proportional to the particle size. The reflected light is measured at right angles to the incident light, detection being accomplished by a photomultiplier tube that provides a pulse whose magnitude is related to the particle size. The aperture is deliberately made small (1 by 2 mm) so that particles generally are counted singly. Particle-size distributions are determined by counting the

full mode (all particles above a set particle size) or by counting a limited mode (all particles within a given particle-size range). The standard particle-size range of 3 to 100 microns is covered in 15 ranges. The Royco instrument would no doubt be suitable for the measurement of particles in storable, compatible propellants, but propellants that react with plastic or quartz must be avoided. Cryogenic fluids have not been analyzed, but appropriate modifications should permit the handling of such samples. The 3-micron minimum-particle-size limit is considerably lower than the 25-micron limit of the Sperry instrument, but is not down to the desired 1-micron measurement. It is noteworthy that light would be reflected from solid-liquid, liquid-liquid, or gas-liquid interfaces and that undissolved impurities having the same refractive index as the suspending medium would not be detected; however, these are not expected to be objectionable or serious limitations.

3. High Accuracy Products Corporation

The HIAC automatic particle counter is based on measurement of the interruption of a light beam by suspended particles. Light from a source is collimated and directed through the fluid stream onto a phototube. As a particle in the fluid stream passes the window, a portion of the light beam is interrupted, causing a change in the phototube output signal proportional to the size of the particle. The signal change is amplified and sent to counter circuits preadjusted to various sensitivities for the simultaneous counting of up to four size ranges within the limits of the microcell being used. The signal is then tallied according to the particle sizes represented. Particles are counted for a measured volume and tallied. They are sized accurately whether light is absorbed, reflected, or refracted. Absolute calibration is achieved using standard particles located on a transparent disk and using a calibrated window such as that employed during sample counting.

The instrument may be used for laboratory or continuous analysis. For on-stream analysis, the sample stream is directed through the counter. Fluid is removed from the stream, is mixed to provide turbulence, and is then passed through the measuring cell. Analyzed fluid is discharged to a graduated cylinder, the volume is measured, and fluid is discarded. The HIAC particle counter is highly recommended by the Millipore Company. Its chief limitations are (a) cryogenics cannot be analyzed, (b) fluids that attack glass or epoxy must be avoided, (c) a small volume of sample is lost during the analysis, (d) the measurement of analyte by using graduated cylinder is crude, (e) the minimum particle size counted is 5 microns, and (f) several microcells are required to cover a wide range of particle sizes. However, these limitations are essentially the same as exist for the other counters. The advantages are (a) counting down to 5-micron particles (as compared with 25 microns for the ultrasonic counter), (b) simultaneous counting of four particle-size ranges, and (c) use of manual controls to compensate for changes in fluid density and color.

4. Phoenix Precision Instruments

The Brice-Phoenix universal light-scattering photometer is a multipurpose, precision instrument for the measurement of transmittance, reflectance, fluorescence, luminescence, turbidity, and reflection from suspended particles. Particle sizes may be calculated from the dissymetry of

light scattering or from the angular distribution of the scattered light. As designed, the instrument is a laboratory tool, but flow cells can be inserted to permit the making of continuous measurements. The instrument would have its greatest use in following changes in particle size, rather than in the absolute measurement of particle size.

5. Coulter Electronics, Inc.

The Coulter counter determines particle size by measuring the change in resistance of a conducting solution. Particles suspended in an electrically conductive liquid are circulated through a small aperture between two electrodes. The aperture is sized so that particles pass through singly. Particle passage displaces electrolyte from the aperture, causing a change in resistance between the electrodes and producing a voltage pulse proportional to the particle volume. The particle-size distribution is determined by counting pulses exceeding a series of threshhold voltages. Instruments presently being marketed require an electrolyte or dispersing medium having rather low resistances, although a Coulter representative states that the electronics have been developed to permit measurements in less-conductive solutions. Nevertheless, the instrument is not currently designed for continuous measurement of particles in a flowing fluid, even though the technique is theoretically adaptable to continous monitoring.

C. HIGH-SPEED PHOTOGRAPHY

In the propellant-test system it will be desirable to make photographic studies of cavitation, erosive and chemical attack, vibration, and the dispersion and flow phenomena of heterogeneous streams. Because of the high velocities employed in fluid pumping, photographic studies will necessarily employ high-speed techniques.

For large moving particles, the maximum exposure time that will yield an unblurred photograph of the object may be approximated by

$$E = \frac{D + F}{S\ 1200\ F}$$

where

E = exposure time, sec
D = distance between object and camera, in.
F = focal length of lens, in.
S = velocity of object as it moves perpendicular to optical axis of camera, in./sec

However, for very small objects, E/10 to E/20 is a better approximation of the effective exposure time. As an example, for a velocity of 50 ft/sec, a 2-in. focal length, at a 24-in. camera-object distance,

$$E = \frac{24 + 2}{600 \times 1200 \times 2} = \frac{1}{55,000}\ \text{sec}$$

For objects of ordinary size or for very small objects,

$$\frac{E}{20} \fallingdotseq \frac{1}{1,000,000} \text{ sec}$$

The rule to follow for selection of the divisor is that the ratio of particle diameter to distance traveled during the time of exposure must be equal to, or greater than, 10.

The above simplified example indicates the need for very short exposure times if photography is to be a useful tool. The methods of obtaining these very short times include the use of

1.   A rotating-prism shutter, in which a four- or eight-sided prism is rotated at high speed, allowing light to strike the film only when opposing prism faces are parallel to the film plane

2.   Stroboscopic light sources, which yield a very high intensity light flash of extremely short duration

3.   A Kerr-cell shutter, in which light passes through a liquid (e.g., nitrobenzene) only when an electric field exists between two plate electrodes placed as opposing faces of a cubic or rectangular cell and parallel to the direction of light travel.

All three of these methods have the effect of "freezing" the motion of moving objects by allowing their viewing only during a period of time that is short in comparison with the time per unit travel distance.

In general, rotating-prism-shutter cameras allow framing rates as high as 25,000 pictures per second (pps) and exposure times as short as 1/1,000,000 sec. Stroboscopic light sources are capable of giving off light for as little as 5 nanosec (5×10^{-9} sec). Kerr cells can yield exposure times as fast as the highest-frequency signal generator will allow (currently, about 3×10^{-12} sec).

There is one basic limitation with regard to the fastest permissible exposure: the inverse relationship of total requisite light energy to film sensitivity. For a given sensitivity, high-intensity, short-duration flashes are interchangeable with an equivalent energy flash of longer duration and lower intensity. For each given total light-energy level there is an optimum sensitivity for obtaining a "good picture."

At pumping velocities of 50 ft/sec, an exposure time of 1 microsec will allow the study of 17-micron particles; with a wide-angle lens utilizing a narrow slit, even greater sensitivity will result. For examining contaminants in the active stream of propellants, framing rates to approximately 20,000 pps should be adequate. Because cameras of this level of performance are readily available, examination of the flow effects mentioned earlier is feasible, as is study of entrained impurities. These cameras must be used with film having ASA speeds of 200 to 1000 and with proper lighting. The items mentioned are standard with many of the companies in the field, and some make developing equipment for normal and high-speed processors.

Table 8 gives information on devices employed for taking high-speed pictures. Accessory equipment (lenses, power supplies, film, developers, etc.) are not reviewed here. These items are also available from manufacturers or representatives listed in Table 30.

D. WATER ANALYZERS

The compatibility and performance of rocket propellants normally depend on the water content; it is therefore desirable to measure this impurity accurately. A wide variety of techniques are available, the method selected being dependent on the chemical and physical properties of the sample. Thus, water in N_2H_4 might be established by means of refractive-index determination, gas chromatography, microwave spectroscopy, or mass spectrometry, whereas water in LO_2 might more appropriately be determined by particle-size analysis or spectrophotometry. Generally speaking, water content may be determined by any of the instrumental methods reviewed in this report. In addition, water may be determined by coulometry, dielectric-constant, radio-frequency power-absorption, heat-of-absorption, or radiation techniques. The principles of these latter methods are discussed briefly below, and the instrument specifications and characteristics are given in Table 9.

1. Coulometry

The electrolysis cell consists of platinum electrodes with phosphorus pentoxide "electrolyte." Sample gas is passed at a constant rate through the cell, and any water present is absorbed and then electrolyzed. The current flowing during electrolysis is proportional to the water content of the sample stream. Instruments of this type are manufactured, under license from Du Pont, by Beckman Instruments, Inc., Consolidated Electrodynamics Corporation, and Manufacturers Engineering and Equipment Company (MEECO). (Leeds & Northrup also holds a license, but has not yet marketed an instrument.) The Consolidated Moisture Monitor for liquids uses a stripper column for separation of water from the sample, after which the nitrogen-water stream passes through a coulometric cell.

2. Dielectric Constant

The dielectric constant is related to the capacitance of a simple electric condenser with parallel conducting electrodes as follows:

$$\epsilon = \frac{4\pi r C}{A}$$

where

    C = capacitance, uuf
    A = area of each electrode, cm^2
    r = distance between electrodes, cm
    ϵ = dielectric constant of substance between electrodes, uuf/cm

Rather than calculate the dielectric constant of a sample on the basis of the measured electrode area, separation, and capacitance, ϵ is conveniently calculated from

$$\epsilon = \frac{C\epsilon_o}{C_o}$$

where C is the capacitance when the space between the electrodes is filled with the test sample, ϵ_o is the dielectric constant of vacuum (i.e., unity), and C_o is the capacitance of the fixed pair of electrodes in vacuum. In a typical application, a fixed pair of electrodes is positioned in the sample stream and the capacitance is monitored continuously. Small changes in the water content are easily detected in most cases, because changes in water content produce relatively large changes in capacitance. The sensitivity of the method decreases as the dielectric properties of the propellant approach the dielectric properties of water or any other impurity that is being monitored.

3. Radio-Frequency Power Absorption

Both Boonton Polytechnic and the Moisture Register Company manufacture moisture analyzers based on the r-f power-absorption principle. For most samples, increasing the water content increases the amount of power dissipated because of increasing electronic and ionic conduction and increasing dielectric hysteresis, the latter resulting from the distortion and orientation of molecules in the sample being tested. By utilizing the proper radio frequency, sufficient power is absorbed by the sample so that sensitive changes in power absorption are detected, permitting water detection down to near 0%.

4. Heat of Absorption

The Mine Safety Appliances Company (MSA) manufactures a water-vapor recorder based on measurement of the heat of absorption of water by an appropriate desiccant. Thermocouples embedded in the desiccant develop an electrical potential that is proportional to the water content. The sensitivity of the method depends essentially on the number of thermocouples embedded in the absorber.

5. Radiation Techniques

The Qualicon bulk-moisture gages marketed by the Nuclear-Chicago Corporation depend on the reflection of neutrons by hydrogen atoms. All materials serve as neutron reflectors to some extent, but hydrogen is by far the most efficient. When all or most of the hydrogen in a system is present as water, the neutron reflection becomes specific for water. Because neutrons are relatively unaffected by environmental factors, moisture measurement is essentially independent of process variables (temperature, pressure, composition, etc.). Many of the propellants contain hydrogen, however, and the method is therefore only applicable in the analysis of perfluorohydrazine, dinitrogen tetroxide, oxygen, nitrogen, fluorine, ClF_3, and similar propellants.

E. SPECIFIC ELECTRODES

Several electrodes have been designed that are specific for various contaminants, such as chloride, hydrogen ion (pH), and oxygen. Methods for determining oxygen other than through the use of the oxygen electrode are also reviewed here. For the most part, measurements using the specific electrodes have meaning only when they are made in aqueous solutions, although there are

exceptions. Oxygen monitors have wider applicability, especially those that measure oxygen in gas streams. The various electrodes and oxygen sensors are discussed below, and the characteristics are summarized in Tables 10 and 11, respectively.

1. Chloride Electrode

Beckman has developed a special silver-silver chloride electrode suitable for continuous chloride monitoring. The special billet is made from silver-silver chloride mixed and pressed into a hard billet. The resulting electrode is structurally sound and is suitable for continuous-monitoring applications when used in conjunction with a reference electrode. The measured potential in millivolts is proportional to the chloride concentration from a few parts per million to 10,000 ppm. Some delay in electrode response is experienced in going from very high to very low chloride concentrations. Sunlight, high solution pH, or other halides affect the accuracy of potential measurements. Other oxidants or reductants in solution affect the measured potential through the introduction of a secondary potential. In view of these limitations and the fact that propellants are nonaqueous, the chloride electrode is not directly useful for propellant analysis.

2. pH Electrodes

Beckman and Leeds & Northrup manufacture special pH electrodes for process-stream monitoring. They also market flow chambers for process-stream applications.

Beckman has three glass electrodes for various applications. The heavy-duty, general-purpose electrode, which is resistant to shock and abrasion, measures pH in the range from 0 to 11 at temperatures from -5 to +100°C. The low-resistance, general-purpose electrode is designed for the measurement of low-conductivity solutions or some nonaqueous solutions in the pH range from 0 to 11 at temperatures from -5 to +100°C. The third electrode is made from E-2 glass for measurement in the high-pH range.

The temperature limit on electrode use precludes the measurement of pH for the low-boiling propellants. One possible application is in the monitoring of H_2O_2 composition. The apparent pH values for neutral H_2O_2 decrease as the H_2O_2 composition increases, as shown below.

H_2O_2, %	Apparent pH
50	2.9
60	2.3
70	1.7
80	1.0
90	0.1

Thus, an accurately measured pH could serve as an indication of assay so long as impurities do not affect the pH more than other compositional changes.

Robershaw and the Bailey Meter Company market instruments for pH monitoring that use Beckman electrodes. Analytical Measurements markets a

recording pH meter; the price of $245 includes the recorder and electrode, but a Beckman or Leeds & Northrup electrode would have to be substituted to permit flow monitoring.

3. Oxygen Electrode

Beckman makes a dissolved-oxygen electrode suitable for the measurement of oxygen in liquid or gas streams. The heart of the electrode is a membrane permeable to oxygen. Oxygen that penetrates the membrane is electrolyzed to provide a measure of oxygen content. Beckman holds the complete rights to this Clark electrode. The Yellow Springs Instrument Company manufactures the electrode under license from Beckman.

4. Other Electrodes

Beckman has developed a CO_2 electrode and a sodium electrode, both of which are expected to be on the market shortly.

5. Oxygen Monitors

The Beckman continuous oxygen analyzer is based on the paramagnetism or positive susceptibility of oxygen. A magnetic field tends to concentrate in the more paramagnetic substances and to repel diamagnetic substances. A test body suspended in the sample-gas stream is attracted or repelled, depending on the presence or absence of oxygen and the amount present. Few interferences are experienced from most gas streams, because most of the common gases (except for nitric oxide) are diamagnetic. Leeds & Northrup also makes a paramagnetic oxygen analyzer designed specifically for the analysis of furnace gases and the like. The sample is scrubbed and otherwise purified before analysis in the measuring cell.

Oxygen monitors manufactured by Greenbrier, MSA, Beckman, and Analytic Systems operate on the galvanic principle. Typically, a potassium hydroxide electrolyte is employed with silver and lead electrodes. Oxygen from the gas sample dissolves, causing ionization of the electrolyte and resulting in an ion current that is proportional to the oxygen concentration.

F. ROBOT CHEMISTS

Robot chemists are devices that automatically perform most of the functions of a laboratory analyst. Typically, the instrument samples from a stream, adds reagents, and determines the optical transmission. A sample may also be analyzed by means of other simple procedures. The capabilities of the various instruments vary, but the range of tasks that may be performed is almost limitless. At times, the instruments have limited versatility in that, for example, a unit set up to measure Kjeldahl nitrogen can perform that analysis only. The limitation is much less severe in the case of automatic colorimeters or automatic flame photometers; simply by making appropriate changes in the reagent type and concentration and in the measuring wavelength, a variety of similar impurities can be measured. The accuracy and sensitivity of a determination usually depend only on the analytical procedure.

Because of the specialized nature of these robot chemists and the large amount of application engineering required, few generalizations can be made, and a comparison of units is less informative than in the case of most other process instruments. Instruments are manufactured by Hagan Chemicals & Controls, Milton Roy, Research Specialities, and Technicon, and are discussed briefly below. Their characteristics are summarized in Table 12.

1. Hagan Chemonitors

The Hagan series of Chemonitors are available for colorimetric, volumetric, and conductivity analysis. The Chemonitor CA duplicates almost exactly the manipulations of laboratory-bench chemistry for colorimetric procedures. Reagents are added and mixed with the sample separately in the sequence established by laboratory practice. Time delays are provided as the chemistry may demand. The Chemonitor CA-D is the basic colorimetric analyzer with continuous distillation apparatus added. The Chemonitor MA is a conductivity analyzer that may be used for accurate control of a process based on conductivity. The Chemonitor VA performs titrations to electrometric endpoints. With only a few exceptions, the Chemonitors have been used in the control of water solutions. The chief limitation is imposed by the Tygon tubing, which prohibits the use of reagents prepared in alcohol or other solvents that attack Tygon; another plastic could be used.

2. Milton Roy Analyzers

The Milton Roy Quantichem and Chemalyzer instruments are designed for colorimetric determinations. The Chemalyzer is simpler, less expensive, and less versatile than the Quantichem, but the Chemalyzer requires no recorder. The two analyzers are compared in Table 12.

3. Research Specialties Automatic Titrator

The Research Specialties instrument differs from other robot chemists in that it does not take samples from a flowing stream, but rather aliquots are pipetted from containers. Measured samples are titrated to an electrometric endpoint, and the information is presented by means of a digital printout or chart recorder.

4. Technicon Autoanalyzer

The Technicon instrument probably is capable of performing more functions than any of the other instruments. The Autoanalyzer is capable of metering reagents, mixing, dialyzing, heating, measuring by colorimetry and flame photometry, and recording the results. Technicon claims that more than 90% of the routine methods may be carried out by Autoanalyzer methods.

G. FLAME PHOTOMETRY

Flame photometry is based on the phenomena that occur in the electronic structure of atoms in a flame. During excitation, electrons receive enough energy from the flame to be raised from one energy level (E_1) to another (E_2). As the electron drops back to its original energy state, a quantum of energy is emitted as light at a frequency given by

$$\nu = \frac{E_2 - E_1}{h}$$

where

ν = frequency, cps
h = Planck's constant, 6.624×10^{-27} erg-sec
E_2 = energy of excited state, ergs
E_1 = energy of unexcited state, ergs

Any one electron can emit only one wavelength at a given instant, but many planetary electrons are present and all can emit radiation of different wavelengths. Thus, emission spectra are observed that correspond to different energy-level transitions. A single strong emission line is utilized for quantitative work. The intensity of emission at this wavelength is measured and compared with the emission intensities of standards.

About 45 elements can be determined by flame photometry. Typical sensitivities, in parts per million, are Na, 0.0002; Ca, 0.003; K, 0.001; Cu, 0.01; Fe, 0.2; Cr, 0.1; Al, 4; Au, 20; and Zn, 500. Samples to be analyzed by laboratory procedures are conventionally dissolved and diluted as necessary in water or another appropriate solvent prior to introduction into the flame. In the analysis of propellants, particularly fuels or heat-sensitive oxidizers or monopropellants, ignition could occur and might necessitate some extra precautions or special design of the sample-handling system. In any case, the technique is useful for following changes in concentrations of metallic contaminants, such as iron or chromium in dinitrogen tetroxide or in fuming nitric acid or other propellants.

Both Waters Associates and Technicon Controls market a process flame photometer. Except for the few changes in design required to permit continuous analysis, each is an automated laboratory flame photometer. In the Waters instrument, liquid sample is fed continuously to a weir, which maintains a constant liquid level and allows the excess to drain off. In the Technicon photometer, instead of measuring emitted light directly, the flame is pocketed in a glass chamber with curved, reflecting walls. The detector receives and measures essentially all the light emitted by the flame. By means of a special design of the oxygen-propane burner, and because the sample is pumped rather than aspirated into the flame, added stability is given to the flame. Characteristics of the two instruments are given in Table 13.

H. X-RAY FLUORESCENCE

If a sample is irradiated with X-rays, planetary electrons are raised to higher energy states by the absorption of energy. Electrons in the excited state then fall back stepwise to successively lower energy levels, with a consequent emission of radiation at each transition. Because the return to the unexcited state involves several steps, each transition results in the emission of radiation at a longer wavelength than the exciting radiation. The X-ray fluorescence spectrum provides a means of analysis for samples containing heavier-element impurities (the absorption of X-radiation by an element is in proportion to its atomic weight). The analysis of low-level impurities is

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limited by the relationship between background radiation and the fluorescence line of the desired element. In favorable circumstances, the limit of detection is as low as a few parts per million.

The X-ray fluorescence technique is limited, generally, to elements of atomic number 13 (aluminum) and higher. Dissolved or suspended impurities such as iron, chromium, iron oxide, tin, aluminum, aluminum oxide, and other likely contaminants may be measured at low levels and up to relatively large concentrations. Special flow cells having "transparent" windows of Mylar or another plastic are required; consequently, only propellants compatible with these windows can be analyzed. The instrument is essentially tailored to the specific system to be monitored, and any versatility desired must be built in during design and installation. Although the technique is not as sensitive as flame photometry, it offers the advantage that more of the elements (about 66) can be determined.

Aerojet has had an X-ray fluorescence unit in use at its Sacramento facility for several years; the specific application is determination of the chloride content of a solid-propellant submix. X-ray spectrometers are available from Applied Research Laboratories, General Electric, and Philips Electronic Instruments. Specifications for models from the three manufacturers are compared in Table 14.

I.   POLARIMETRY

Substances that rotate the plane of plane-polarized light generally have an unsymmetric carbon atom and are termed "optically active." The measurement of rotation is called polarimetry. Many organic substances possess the required asymmetric carbon atom - one with four different groups bonded to it - and thereby the concentration of the compound dissolved in solute may be determined from angular degrees of rotation, assuming that the appropriate constants are known. Most of the propellants currently in use are simple compounds; thus, the measurement or monitoring of optical rotation will be of value in very few cases.

Only one process polarimeter is presently known, that of the Bendix Corporation. Du Pont has a continuous polarimeter in the development stage, but its specifications are not yet available. Characteristics of the Bendix polarimeter are discussed below and presented in Table 15.

In the Bendix instrument, conventional Polaroid or Nicol polarizers are replaced by Faraday cells to provide automatic balancing. Light from the source traverses an interference filter, polarizer, modulator Faraday cell, short-path flow-through cell, compensator Faraday cell, and analyzer, finally striking the photomultiplier. Current from the compensator Faraday cell provides a millivolt signal for data recording. Colored or nearly opaque solutions are measurable as long as the transmittance is greater than 10%. Solid or particulate matter must be removed. Analyses are rapid (10 sec) but, for the best results, sample flow should be stopped during measurement. Only a small amount of sample is required to fill the 5, 10, or 20-mm-long by 8-mm-dia flow-through cells.

J.   REFRACTOMETRY

The refractive index, a physical constant characteristic of chemical compounds, is defined as the ratio of the velocity of light in a vacuum to the velocity in the substance measured. Refractive-index values all are greater than 1, which is the refractive index for a vacuum. The refractive index of water is 1.333 at $25^{\circ}C$, and the refractive index of several typical propellants is about 1.45 (N_2O_4, 1.420 at $20^{\circ}C$; N_2H_4, 1.4644 at $25^{\circ}C$; UDMH, 1.4508 at $25^{\circ}C$; B_5H_9, 1.4445 at $24^{\circ}C$).

Because of the extreme accuracy obtainable in these measurements, the water content of the above and many other propellants may therefore be determined from refractive-index values, assuming that close control of other interfering variables is maintained. If water is the contaminant being monitored, the presence of varying amounts of a second impurity generally constitutes interference, but the refractive index still is a useful guide to the purity of the major component. In propellant analysis, refractive-index measurements may be used to determine impurity levels or the ratios of two ingredients in mixed propellants. For meaningful values to be obtained, it is necessary to control or compensate the temperature, wavelength, and other parameters whose change causes variations in the indicated refractive index.

Laboratory instruments are used to determine the refractive index by measuring the angle of refraction of light at the sample-prism interface as light traverses the sample. Differential refractometers achieve greater flexibility through continuous comparison of the sample and reference at the same temperatures. Small differences in the refractive index are detected and amplified to provide greater accuracy and sensitivity of measurement. The Optics Technology, Daystrom, and Waters instruments are unique in that the index of a sample is determined by the immersion of a single element in the sample stream; they measure the refractive index without transmission of light through the sample. Five refractometers are compared in Table 16 and are discussed below. Discussions of the Bausch and Lomb and the Phoenix Precision instruments were omitted because production of the former was discontinued and information is lacking on the latter.

1.   Barnes Differential Refractometer

In the Barnes refractometer, light from a high-intensity mercury lamp is collimated by a lens system on the differential-prism cell. After passing through the cell, the radiation is reflected back through the cell for a second traversal of the sample and the reference standard. The beam is then divided into two beams, one directed onto each of the two barrier-layer photocells. One half of the differential-prism cell is filled with the reference standard, and the sample flows continuously through the other half. Any change in the refractive index of the sample causes a deviation of the light beam, resulting in an unbalanced signal in the detector circuit. This signal is amplified and transmitted to the servo-system, which determines the signal polarity and drives the restoring plate to bring the system into balance. The angular position of the restoring plate is a measure of the difference between the refractive indexes of the standard and the sample.

Differential instruments are superior to conventional refractometers in accuracy and in simplicity of temperature control. The ambient temperature need not be closely controlled. It is only necessary that the difference between the temperatures of the sample and the reference liquids be 0.2°C or less.

2. Mine Safety Appliances Process Refractometer

The MSA instrument is also a differential refractometer. The principle of operation is identical to that described above for the Barnes refractometer.

3. Optics Technology Refractometer

The Optics Technology continuous-control refractometer makes use of the dielectric-rod photorefractometer principle. The refractometer consists of two units - a sensing probe installed in the process stream through a standard 1-in. pipe fitting, and a power amplifier remotely connected to the sensing probe. The output of the power amplifier is a continuous electrical signal that is directly proportional to the refractive index of the liquid passing the probe. The accuracy is unaffected by entrained bubbles, fine suspended solids, turbulent flow, opacity, or ambient light. A built-in temperature-sensing probe corrects for changes in the refractive index for process temperatures as high as 212°F.

4. Waters In-Line Refractometer

In the Waters refractometer, light from an incandescent lamp is directed through a lens to a prism in contact with the liquid stream. The light beam is refracted at the prism-liquid interface and is directed back to the two photocell detectors. (At angles smaller than the critical angle, the light is transmitted into the liquid; at angles larger than the critical angle, it is totally reflected.) One photocell is located in the reflected-light region, and the other is located at the critical angle. As the refractive index of the process liquid changes, the critical angle changes, causing more or less light to fall on the sample photocell detector. Changes in light intensity at the detector photocell are compensated by a servo motor that drives a glass restorer plate. The amount of movement to restore an optical null is a measure of the refractive index.

In addition to the refractometer described above, Waters manufactures a differential refractometer that incorporates principles of the Barnes and MSA refractometers. Six ranges are available, corresponding to 0.0001 to 0.0000015 RI per recorder division and 0.02 to 0.0003 RI full scale, respectively.

5. Daystrom Indexometer

With the Daystrom Indexometer, light from an incandescent lamp travels through slit apertures and is broken into angular, sweeping pulses at 240 cps by a rotating chopper prism. The scanning beam is then focused at the interface between the liquid stream and a hemispherical prism so that the optic axis of the sweeping light is focused at the critical angle. The beam scans equally on both sides of the critical angle and the phototube output

changes abruptly each half cycle - from very small to maximum. At the critical angle, most of the light is refracted into the process stream during the first half of the cycle, and maximum light is reflected to the phototube during the second half cycle. Deviation in the critical angle from a calibrated setting results in a phototube maximum-output period totaling more or less than half of the scanning cycle, indicating a change in the refractive index. Variations in pulse width are therefore directly proportional to changes in the refractive index of a liquid stream and may be used for continuous indication or recording.

K.   COLORIMETRY

Absorption spectrophotometry is based on the ability of atoms or molecules to absorb light of specific wavelengths. Ultraviolet and visible absorption spectra are characteristic of electronic transitions in atoms, whereas infrared spectra result from vibration and other distortion of molecules. The wavelength range from 400 to 700 millimicrons comprises the visible region, with longer wavelengths designated as infrared and shorter wavelengths as ultraviolet.

The measurement of color or changes in color often serves to indicate the quality of a propellant, as evident from the large number of military specifications that include "color and workmanship" tests. The measurement of color in UDMH is typical of the value of the technique. Pure UDMH is colorless; on standing, the fuel turns to a yellow to reddish-yellow color due to the formation of impurities through oxidation. The color intensity is directly proportional to the contaminant level. The technique can be used similarly for other systems in which impurities impart color to the propellant. When several impurities are present and each has its own distinctive color or absorbance region, each can be determined separately after suitable calibrations at the appropriate wavelengths. Unfortunately, commercial colorimeters do not always provide sufficient resolution to permit the monitoring of two (or more) impurities that produce overlapping absorption peaks. In many cases the ultraviolet absorptions are similarly unresolved, whereas infrared absorptions are better resolved and more readily identifiable with a specific compound or functional group.

Continuous colorimeters are available from Hallikainen, Beckman and the Photovolt Corporation; several nondispersive analyzers measuring in the visible range are described in Section IV,L, following. Colorimeters may be utilized for the monitoring of liquid or gas streams. Whenever desired, liquids may be vaporized prior to analysis. In most cases the color or turbidity of a solution can be measured by judicious selection of the measuring wavelength. The characteristics of several colorimeters are presented below and are compared in Table 17.

1.   Hallikainen Color Analyzer

The Hallikainen color analyzer is a differential photoelectric colorimeter designed especially for determination and recording of the color of petroleum products and other liquids. Light from the incandescent source passes through a flow-type sample cell and to the detector phototube. Calibration of the instrument is accomplished by the use of ASTM color standards.

2. Beckman Turbidimeter-Colorimeter

The Beckman continuous colorimeter-turbidimeter is constructed as two units, the analyzer unit and the control unit. Within the analyzer unit, light is passed through the sample in the flow-through cell. Light reaching the detector phototube is measured and converted to a signal that is amplified in the control unit to drive a direct-reading meter, potentiometric recorder, or alarm circuit. The proper choice of interference filters, phototube, and sample cell path makes the Model 77 specific for color (of a narrow wavelength, if desired) or turbidity.

3. Photovolt Continuous-Flow Colorimeter

The Lumetron continuous-flow colorimeter is suited for continuous registration of the concentration, color, or turbidity of non-corrosive solutions. The light transmission of the liquid stream is registered continuously as the liquid passes through the instrument. Light from a stabilized incandescent lamp is collimated, passes through a color filter, and then traverses the flowing sample. The attenuated light beam then impinges on a barrier-layer photocell detector. The current from the photocell is registered by an indicating meter.

L. NONDISPERSIVE PHOTOMETRY

Nondispersive photometry differs from conventional spectro-photometry in that polychromatic light from the source is used for sample irradiation. No prisms or gratings are incorporated to provide monochromatic or narrow-band radiation; the instrumentation is therefore greatly simplified. Radiation absorption is measured at a fixed wavelength, and spectrum scanning is therefore not provided. Instruments are available for the making of measurements in the ultraviolet, visible, and infrared regions. The ultraviolet and visible photometers generally employ filters to permit passage of the proper wavelengths to the phototube detectors, whereas infrared photometers employ gas-filled chambers as selective filters. Detectors incorporated in infrared photometers are usually of the pneumatic type, and measure detector-cell volume and/or pressure changes resulting from varying amounts of radiation passing through the sample. These detectors are sometimes Golay-cell pneumatic detectors.

Nondispersive analyzers are capable of extreme sensitivity when properly applied to the specific analysis, as may be seen in Table 18. The samples to be analyzed may be liquids or gases, although these instruments have preponderently been applied in gas analysis. In adapting nondispersive photometers for propellent analysis, the compatibility of the sample with the cell optics is of critical importance. The mechanical strength, chemical resistance, and transmission range of sapphire make it suitable for almost all applications. For the analysis of fluorine and ClF_3, calcium fluoride windows provide a satisfactory alternative.

Nondispersive analyzers are available from Hallikainen, Du Pont, Analytic Systems, MSA, Beckman, and Leeds & Northrup. The Hallikainen ultra-violet analyzer is a simple differential photometer, as is the Du Pont photometric analyzer for color analysis. Analytic Systems manufactures four

nondispersive analyzers. The Model 500 is for near-infrared use, whereas the Models 600 and 650 are for ultraviolet. The Model 700 is an infrared photometer. Three LIRA infrared photometers are marketed by MSA. The Model 100 provides extreme sensitivity; lesser sensitivity is achieved in the Models 200 and 300. Beckman and Leeds & Northrup also make nondispersive infrared analyzers. Specifications for these various instruments are given in Table 18.

M. RAPID-SCAN SPECTROPHOTOMETRY

Rapid-scan spectrophotometers have advantages in certain applications as opposed to laboratory spectrophotometers or fixed-wavelength monitors. Laboratory spectrophotometers are satisfactory for many analyses, but a rapid-scan spectrophotometer is desirable when fast reactions or rapid liquid flow may change component concentrations rapidly. Continuous analyzers might serve as well where only the concentrations of known components are of interest; if a new compound is anticipated, however, rapid-scan spectrophotometers are indispensible for a complete evaluation of the system. Applications might include a study of rates of reactions between propellant and impurity, corrosion studies, etc. in liquid or vaporized propellant systems.

Block Engineering manufactures several interferometer spectrometers, each covering portions of the spectral region from 0.35 to 40 microns. The interferometer serves as a sensor to measure radiation from a body or to determine the transmission of an absorbing sample. For chemical-analysis applications, a light source and a sample cell must be provided. In order to obtain the conventional spectrogram readout, the electrical signal must be converted by means of a wave analyzer. Because all wavelengths are scanned simultaneously and spectral information is converted into electrical frequencies, regions of special interest can be monitored simultaneously by electrical filters in parallel at the output of the detector. This in no way interferes with high-resolution spectral data obtained in scanning. These interferometers and their performance are described further in Ref. 9, and specifications are given in Table 19.

Baird-Atomics, Bausch and Lomb, Leeds & Northrup, and Unicam do not make rapid-scan instruments. American Optical made a rapid-scan spectrometer until recently. The instrument measured transmittance in the visible range from 400 to 700 millimicrons at a rate of 60 scans/sec. The cathode-ray-tube presentation gave a continuous display. The instrument cost $1300; the last one was sold a few months ago (in 1962), and American Optical evidently does not intend to continue production. However, past production of rapid-scan spectrophotometers indicates capability in the field and perhaps the firm would be willing to consider special orders for such units.

Beckman has also worked in the field of rapid-scan spectrophotometers, for ultraviolet, visible, and infrared analysis. The firm does not have instruments presently available, but has made special units in the past and is willing to undertake development projects.

Rapid-scan spectrophotometers whose production has since been discontinued are discussed in Refs. 10 and 11.

N.   TURBIDITY

Turbidity results when two substances are mixed but do not dissolve in each other. The attending cloudiness is caused by the reflection of light from the surface of the suspended second phase, which may consist of undissolved solids, liquids, or gases. Light from an appropriate source is passed through the process stream and the intensity is measured. Reductions or changes in the intensity of light at the detector correspond to changes in the turbidity level, assuming that other factors (changes in solution color, temperature, density, etc.) are controlled or compensated. Measurements of particulate contaminants may be made in this way, but such measurements are subject to interference from suspended liquids, which might be present when propellants are cooled sufficiently to give phase separation. Theoretically, the turbidity of cryogenics can be measured, but provision must be made to prevent the external frosting of optical windows through the condensation of moisture or other atmospheric constituents.

The Jacoby-Tarbox turbidity meter is the only instrument known to have been designed specifically for the continuous monitoring of turbidity. However, the continuous colorimeters discussed in Section IV,K, above, can be utilized for turbidity measurements in most cases. Characteristics of the Jacoby-Tarbox instrument are discussed below and are summarized in Table 20.

The Jacoby-Tarbox industrial turbidity indicator-controller will continuously monitor the turbidity, cloudiness, or haze of a liquid by direct measurement in the process pipeline. The complete system consists of a flow cell, a light source, a photoelectric scanner, and an indicator/controller unit. The light source and photoelectric scanner are mounted on opposite sides of the flow cell, which is mounted as part of the flow system. Windows are available in quartz or Vycor with Teflon gasketing. The instrument is available with double windows to prevent frosting at low temperatures.

O.   DENSITY

In most instances of propellant contamination, the density of the impurity is different from that of the propellant; thus, a measure of density or changes in propellant density serves as an index to the quality of the material being tested. Considering the physical nature of density measurements, it is conceivable that two impurities - one of higher and one of lower density - might be added so as to reflect no change in composition, but such an occurrence is unlikely. The addition of insoluble or undissolved solid, liquid, or gaseous impurities would likewise affect propellant quality, but the presence of such impurities is detected by the several density-measuring devices available. Techniques for the continuous measurement of liquid density include (1) the attenuation of nuclear radiation, (2) the weighing of a sample loop, and (3) the damping of a vibrating probe. These three principles are discussed below, and available instruments are compared in Table 21.

1.   Nuclear Densitometers

Nuclear density gages usually employ beta or gamma radiation sources. Gamma-ray instruments are used almost exclusively in industrial

process-stream applications because of the greater penetrating power of gamma rays. The fraction of emissions reaching a scintillation counter from a known radiation source is inversely proportional to density, assuming that the sample thickness and other parameters are constant. For materials having specific gravities from 0.8 to 1.5, a path length of 6 to 14 in. is suitable. Commercial instruments are available for pipe diameters down to 3 in. Changes in the pipe diameter or density range are accommodated by changing the source size or the thickness of the lead shielding.

The Nuclear-Chicago Qualicon Duo unit is a two-piece instrument consisting of a source and a detector. A highly collimated γ-ray beam is directed across the stream to the detector. For diameters of less than 3 in., a Z-shaped pipe section of appropriate length may be employed, whereupon gamma radiation is directed parallel to the axis of the line. In this latter configuration, the minimum pipe diameter is about 3/4 in. The Ohmart Model ASR-3 and the Industrial Nucleonics DH-3 are specifically intended for use on 3-in. pipes, or smaller. In the Ohmart instrument, the source and detector are delivered mounted on a Z-shaped section of pipe and ready for installation. The Ohmart and the Saunders-Roe density gages also incorporate a reference source of cesium 137 to compensate for drift and changing radio-activity level.

2. Weighing Densitometers

The Arcco Instrument Company manufactures the Arcco-Anubis liquid gravitometer for monitoring the specific gravity of liquid streams. The instrument consists of a 1-liter sphere suspended at the end of 2-ft-long, stainless-steel, flexible, inlet and outlet tubes. The vertical motion of the bulb resulting from changes in the specific gravity of the process liquid is recorded. In operation, the flow of liquid is increased to the point of turbulence, and the velocity is then slightly decreased for measurement or monitoring. The minimum desirable flow rate is 1000 cc/min, thus providing a complete volume change each minute. The Rotameter Manufacturing Company of Croydon, England has also developed a weighing densitometer wherein a hairpin loop is weighed continuously. The two 5-ft lengths of 1-in. pipe are connected to the main stream by means of flexible connections. The entire loop is suspended from a weighing beam. Any change in stream density causes a corresponding change in the weight of the loop.

3. Vibration-Damping Densitometer

The Automation Industries Dynatrol gravitometer determines fluid density by measurement of the damping effect on a paddle inserted in the flowing stream. A driver coil produces a 120-cycle vibration in the paddle. The pickup end contains a permanent magnet and coil that provide an output signal proportional to the amplitude of the paddle vibration. The output signal reflects the properties of the medium surrounding the paddle. This principle has been employed in the development of a series of detectors available in a wide selection of ranges, responses, and sensitivities for the measurement of density, viscosity, level, and interface.

P. VISCOSITY

The viscosity of a fluid process stream is likewise an important index of composition or purity. In the case of typical liquid propellants, viscosities range from 0.509 centipoise (cp) for UDMH (25°C) to 0.90 cp for N_2H_4 (25°C). The viscosity of water as a typical impurity is 0.895 cp at 25°C. Thus, viscosity measurements might be used to determine water in UDMH but not in N_2H_4. The composition of a binary mixture such as UDMH-N_2H_4 can be monitored, assuming that impurities are absent or do not have an adverse effect on the viscosity-composition relationship. Changes in viscosity might result from polymer formation arising out of γ-irradiation or other catalytic action, and it might be desirable to monitor such changes. In most cases undissolved impurities will also affect the measured viscosity; inasmuch as viscosity changes greatly with small fluctuations in temperature, close control or compensation of this variable is required.

A wide variety of instruments and techniques are available for continuous monitoring of process-stream viscosity. The known instruments are described below and are compared in Table 22.

1. Hallikainen Continuous Capillary Viscometer

The Hallikainen viscometer is designed for use on Newtonian liquids (fluids whose viscosity does not vary with shear rate), although non-Newtonian products may be monitored if a viscosity determination at one shear rate will provide adequate information. The metering pump built into the instrument requires that the fluid to be measured have lubricating properties. A sample is forced through a capillary tube at constant flow, using a gear pump driven by a synchronous motor. The pressure developed across the viscometer is proportional to the viscosity.

2. Norcross Falling-Plunger Viscometer

The Norcross viscometer incorporates a piston inside a tube as the measuring chamber. The piston assembly is lifted by an air-cylinder mechanism and then released, allowing the piston to fall by gravity. At the end of the fall, a proximity switch is actuated to reset the piston and repeat the operation. The time of fall or the number of transits in a given time interval is proportional to the viscosity. The clearance between the piston and the inside of the tube forms the measuring orifices. The plungers may be changed to accommodate high or low viscosities.

3. Bendix Vibrating-Probe Viscometer

The Bendix Ultraviscoson employs a vibrating probe that is pulsed with a short 28-kc signal. When the amplitude of vibration has fallen to a set level because of the damping effect of the liquid, the probe is pulsed again automatically. The damping is proportional to the absolute viscosity and the density of the fluid, and is measured by the rate of pulsation.

4. Automation Products Vibrating-Probe Viscometer

The Dynatrol, described previously for density determinations, may also be used for viscosity measurement. The amplitude of vibration of the paddle varies with changes in the viscosity of the medium in which it is immersed. Compensation for viscosity changes that accompany temperature changes may be made by immersing a second probe in a reference sample maintained at the same temperature as the measured sample. Changes in sample viscosity are then measured by differences in the signals from the two units.

5. Brookfield Rotational Viscometer

The Brookfield Viscometran is essentially the laboratory rotational viscometer mounted on a process line. Flowing sample is brought into a sample chamber (where the flow rate is reduced) and exits out the side port. A spindle, suspended in this sample chamber, is driven at a constant speed by a synchronous motor through a beryllium-copper spring. As the viscosity of the sample changes, viscous drag on the spindle will flex the spring to a new position. This flexing of the spring deflects a set of condenser plates attached to the "free" end of the spring, and the new position creates a new capacitance value for the condenser assembly. A linear relationship exists between viscosity and capacitance, and the output may be recorded by means of any standard capacitance-accepting recorder, such as the Foxboro Dynalog, or others discussed in Section IV,D, foregoing.

6. Precision Scientific Development Capillary Viscometer

As with the Kallikainen instrument, viscosity is determined on the basis of the pressure required to maintain a constant rate of flow through a capillary. Prior to pressure (viscosity) measurement, a sample is taken from the process line, filtered if necessary, and brought to a constant temperature. The measured sample may be discarded or returned to the process line by means of an auxiliary pump.

7. Epprecht Rotational Viscometer

The Swiss-made Epprecht viscometer is marketed in the United States by the J. W. Fecker Division of the American Optical Company. The Model RM-15 is the most versatile of five viscometers manufactured by Epprecht. The principle of operation is the same as for the Brookfield instrument. Visual readout is provided, but a potentiometer recorder is available as optional equipment. The instrument is not normally used for continuous flow monitoring, but there are several variations that may readily be adapted to in-line monitoring.

8. Fischer & Porter Viscometer

The Fischer & Porter Company makes a variety of Viscorators. The single-float Viscorator is a direct-reading instrument. A positive-displacement pump is provided to maintain a constant rate of sample flow through the meter. The float is sensitive only to changes in viscosity, assuming that neither temperature nor density change. The two-float Viscorator is basically the same, except that the second float is sensitive only to the flow rate. The Auto-Sampling Viscorator consists of a constant-flow regulator and a

variable-area type of viscosity float. The latter type is somewhat more suitable for measurements on propellant because the sight glass can be eliminated. The Auto-Sampling Viscorator is available in a model that permits temperature compensation and the recording of viscosity.

Q.   CONDUCTIVITY

The electrical conductivity of a liquid depends on the type and concentration of the ionic species that are present. Most pure liquids have relatively low conductivities, but many impurities dissolve to yield ionic solutions with greatly increased conductivity. Small ions, such as proton or hydroxyl ions, are more mobile than the larger metal ions, and thus contribute relatively more to solution conductivity at comparable concentrations. However, conductivity is a nonspecific property, permitting only a gross measurement of impurities without positive identification of the specific contaminant present.

The conductivity of storable propellants is likely to be a useful index of propellant purity. The normally low conductivity of pure propellants such as H_2O_2, N_2H_4, and N_2O_4 would increase in proportion to the concentration of ionic contaminants such as acids or other dissociable compounds. In some cases, increases in water content might be determinable through conductivity measurements. It is highly unlikely that changes in impurity levels will alter the conductivity of the cryogenic fluids such as oxygen, hydrogen, or nitrogen.

A Wheatstone bridge is commonly used to measure the conductivity of a sample. Satisfactory bridges are manufactured by Industrial Instruments, Foxboro, Leeds & Northrup, the Bailey Meter Company, The Bristol Company and Radiometer of Copenhagen. A typical bridge has a resistance range from 1 milliohm to 1 megohm (100 mhos to 1 micromho), although such a wide range is not generally required because the cell geometry may be selected to permit accurate readings over a narrower range. Indicating bridges manufactured by the companies mentioned above are compared in Table 23. Conductance bridges are available from many other companies as well.

A unique "electrodeless conductivity system" is marketed by Industrial Instruments. It determines the resistance of a flowing stream by measuring the extent to which the sample loop couples two transformer coils. A high audio-frequency signal in the primary loop is detected in the secondary loop. The instrument is designed to monitor solutions flowing through nonconductive tubing (glass, polyethylene, Teflon, etc.). However, manufacturers' representatives claim that none of the liquid propellants is conductive enough to permit the use of the instrument for propellant monitoring.

R.   MICROWAVE SPECTROSCOPY

Microwave spectroscopy (sometimes called radio-frequency spectroscopy) has come to prominence since 1946. Equipment designed for radar systems has since been extended, improved, and refined to permit measurements over essentially the entire range of frequencies. The microwave region lies between radio frequencies and infrared frequencies - from 1000 mc or 1 gigacycle (gc) to 300,000 mc or 300 gc (1 mm to 30 cm) - and hence the methods employed

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and phenomena observed in microwave spectroscopy resemble those associated with both radio-frequency and infrared spectroscopy.

Microwave determinations are used to measure and record pure rotational spectra of molecules, and consequently resemble determinations made on the basis of infrared spectroscopy with its measurement of vibrational spectra. Samples are handled as gases at low pressures in long-path cells. (No sharp-line spectra of liquids have been observed in the microwave region.) Because of the very wide range of the microwave region and the good resolving power of microwave detectors (a wave number of 1/60,000 as compared to a wave number of unity for infrared), approximately 500,000 compounds could have spectra that do not overlap. One absorption line is very often sufficient to provide positive identification of a compound, and three lines are almost always sufficient. Quantitative analyses are made on the basis of measurements of microwave power absorption. The following absorption equation is used to calculate exact results:

$$I = I_o e^{-\gamma X}$$

where

I = intensity of emerging radiation, lumens
I_O = intensity of incident radiation, lumens
X = cell length, cm
γ = absorption coefficient, cm^{-1}

The total number of gases that may be analyzed by this technique depends only on the selection of gases (or volatiles) that exhibit microwave spectra. Complex mixtures do not interfere with this technique. Gases that do not exhibit microwave spectra are the simple symmetric molecules (CH_4, CO_2, H_2, C_2H_4, noble gases, etc.) and molecules with very small moments of inertia (such as HCl and HF). The following compounds are representative of gases that exhibit microwave spectra: H_2O, NH_3, NO_2, NO, N_2O, CO, H_2S, SO_2, O_2, O_3, halogenated aromatics and aliphatics, aromatic and aliphatic acids, aldehydes, ketones, and alcohols. Microwave spectroscopy would therefore be invaluable for characterizing a propellant such as dinitrogen tetroxide (NO_2, NO, H_2O), but not so helpful in the analysis of fluorine (F_2, HF, O_2, N_2, CO, CO_2, CF_4).

Because the rotational energy levels of a molecule are degenerate in the absence of an external field, microwave measurements are often made in the presence of a strong electric field. This Stark modulation improves the sensitivity and utility of microwave spectra. Microwave measurements are sometimes made in the presence of a strong magnetic field so that the Zeeman effect can be observed.

More than 700 companies are currently manufacturing microwave components for one use or another, the vast majority of them for the region below 100 gc. Only one is known (Tracerlab) that actually assembles the required oscillators, amplifiers, wave guides, power dividers, detectors, etc. to produce commercial microwave spectrometers covering a reasonably large portion of the microwave region. Characteristics of the Tracerlab microwave spectrometers are given in Table 24.

The Southwest Research Institute has built several microwave spectrometers for use in its own laboratories and would be willing to contract for the construction of a microwave spectrometer to the user's specifications, if all the required components are commercially available.

S.   GAS CHROMATOGRAPHY

Gas chromatography is a relatively new technique that has attracted widespread attention. A sample introduced at the head of a separatory column is eluted by means of a carrier gas; the components are thereby separated from one another and are sensed as they are eventually swept out the end of the column. Proper chromatographic technique requires the selection and control of the partitioning or adsorption agent, carrier gas, flow rate, column tempera- ture and length, and detector type. Most conditions are dictated by the type of sample and number of components being measured.

Process chromatographs are essentially laboratory instruments designed for continuous and automatic operation. The method of sampling and the course followed by the sample after it is taken from the flowing stream may vary considerably, depending on the equipment employed. Automatic-sampling valves may be incorporated in the fluid-flow system, in which case the gas is injected directly into the head of the column; if the sample is liquid, the liquid is injected into a heated section at the head of the column. The various automatic-sampling valves are compared in Table 25.

Alternately in the handling of liquids, samples may be drawn from the flowing stream, volatilized in a "vaporizer regulator," and then injected into the chromatograph as a gas. Specifications for several of the available vaporizer regulators are given in Table 26. Vaporizer regulators have wider application than merely to gas chromatography. A wide variety of analytical instruments surveyed here require sample in the vapor state, or function best when that is the case. Thus, the vaporizer regulator would find use in the preparation of a sample for moisture measurement (in some applications), non- dispersive photometry, rapid-scan spectrophotometry, microwave spectroscopy, gas chromatography, and mass spectrometry. Additional advantages are possible in that particulate impurities often remain behind during vaporization and that bothersome impurities may be removed by scrubbing or adsorption after volatilization.

Process chromatographs are manufactured by Beckman, Consolidated Electrodynamics, Greenbrier, and MSA. (Several other companies also make thermal-conductivity analyzers.) The specifications for comparable models from each company are given in Table 27. Foxboro has marketed a process chromatograph in the past, and will have a redesigned model on the market in the near future, but information on this instrument is not presently available.

T.   MASS SPECTROMETRY

The mass spectrometer is an instrument for ionizing and sorting out molecules according to their masses and charges. Gaseous sample is intro- duced to an ionization chamber wherein a stream of electrons from a heated filament bombards and removes electrons from the sample molecules. The

positively charged particles are accelerated into the evacuated analyzer section, where the various molecular fragments are separated (1) by means of an electromagnetic field (direction-focusing instruments), or (2) because of differences in the velocity of ions having the same energy (velocity-focusing instruments). The number of particles reaching the detector is measured and recorded or displayed as signal intensity vs mass-to-charge ratio.

The several process mass spectrometers reviewed in Table 28 are used routinely for the continuous analysis of gases. Gases are drawn directly into the handling system; liquids (or solids) that may be vaporized easily at or near room temperature are volatilized prior to introduction into the spectrometer. A wide range of component concentrations may be accommodated - from parts per million to higher percentages - and the mass spectrometer thus serves for the identification and measurement of all but the "nonvolatile" components (the new spark-source instruments are not designed for process work). Typically, a sample of hydrazine may be analyzed to give the N_2H_4, H_2O, and NH_3 content, but sand would not be detected. In the analysis of LO_2, particulate matter consisting of water or CO_2 would be measured because sample treatment would convert these solids to gases. Great difficulty would be experienced in the analysis of H_2O_2, inasmuch as the propellant decomposes easily on heating and a representative sample would therefore be difficult to obtain. Propellants containing fluorine present special difficulties because of their attack on the filament, glass components, and charcoal trap (when such a trap is employed). The specific advantage of mass spectrometry is that the positive identification of impurities and measurement of concentrations are easily accomplished, in contrast to many other techniques in which only a quantitative analysis is practical.

A number of companies manufacture mass spectrometers, but only the three instruments reviewed in Table 28 are claimed by the makers to be process analyzers. The three represent rather wide ranges of prices, types, and capabilities.

U.   WINDOW MATERIALS

Many of the process instruments reviewed in preceding sections employ optical or window materials that must contact the propellant stream. In most cases, when the standard component is not compatible with the propellant of interest, substitutions can be made to suit the application. Ideally, the optical materials would be (1) transparent through the ultraviolet, visible, and infrared regions, (2) compatible with all propellants, (3) mechanically sound at all the required temperatures, (4) of the proper refractive index, and (5) available in any required size.

Inasmuch as a single material does not have all the desirable properties, the windows or optics must be selected to fit the application. For the systems of interest here, two sets of materials will be adequate. Sapphire windows are satisfactory for use with all the propellants except fluorine and ClF_3. (Quartz compares favorably with sapphire in all respects except in infrared transmission.) Calcium fluoride windows are suitable for systems in which these two propellants are handled. Important parameters of these and other commercial materials are compared in Table 29; the list of suppliers given there should be considered as typical rather than complete.

The cell made of sapphire and Teflon described in Ref. 12 would be satisfactory for many situations in which a flow cell is not required. A similar cell could no doubt be constructed for continuous analysis of propellant streams. The Limit Research Corporation recently marketed a low-temperature infrared unit that consists of a cell inside a low-temperature jacket. At low temperatures the jacket is evacuated to prevent moisture condensation. The cell has been used successfully down to $-160^\circ C$, and for this work is fitted with silver chloride, cesium iodide, or cesium bromide windows. The same design could be adapted to the construction of a low-temperature flow cell. Hofman Laboratories supplies helium-research Dewar vessels having 2-in. observation ports with sapphire windows; the prices range from \$2500 to 2800. Dewar vessels have been built by NASA with quartz or Pyrex windows up to 8 in. in diameter for use in photographing cavitation phenomena at LN_2 temperatures; quartz disks were used for camera windows and Pyrex for source windows. In a private communication from the NASA Lewis Research Center, it was reported that Pyrex windows are inferior in optical clearness, but the cost is approximately one-tenth that of the quartz disks.

V.   CONCLUSIONS AND RECOMMENDATIONS

A.   CONCLUSIONS

With regard to many facets of the proposed system, prior direct experience is either minimal or lacking altogether. Analysis of the engineering problems associated with the system resulted in the conclusion that the system is practicable and that most of the requisite equipment is commercially available, as noted in Table 30. If high levels of automation and convenience factors are not necessary, the cost of the facility should not be excessive as compared with the normal cost of rocket-test equipment.

Compatible materials can be obtained for all propellants. Vessels, piping, pumps, and auxiliary equipment can be supplied in these materials. High-efficiency filters, flow meters, and pressure- and temperature-measuring instruments can be obtained without abnormal delay and with good supplier service assured. Liquid-level control can be achieved by the use of a tank weighing system.

The system can be constructed to provide minimum loss of cryogenic vapors due to heat flux; released vapors can be disposed of conveniently. Vacuum equipment can be obtained that will permit rapid evacuation for testing or for thermal insulation, and means have been provided to avoid contamination of the vacuum pumps.

A propellant-contaminant-addition device was designed that will permit the controlled addition of liquid, solid, or gaseous contaminants to the propellant. A prototype unit for this purpose is being constructed to demonstrate the feasibility of this key part of the assembly.

A wide variety of on-stream analyzers are available from manufacturers listed in Table 30 and are directly applicable to analysis of the storable propellants, with the possible exception of ClF_3. Cryogenic propellants and excessively corrosive storables may be most conveniently analyzed as gases, because the analyzer is then subjected to less severe conditions.

In most cases, process analyzers have not been called upon to operate at low temperatures, but in many cases the instrument is adaptable to low-temperature conditions. Many on-stream analyzers can perform as required in the analysis of propellant, if a suitable sample-handling system is constructed or if the necessary application-engineering effort precedes installation. The chief limitation on the extent of instrumentation to be used in a propellant-test apparatus will be one of funding, rather than the availability (either directly or by suitable modifications) of useful equipment. A few items, such as isokinetic-sampling probes and suitable visual-observation windows, are not commonly available. These can be fabricated at reasonable cost, however, by several companies familiar with the refinements involved in the handling of hazardous chemicals.

B. RECOMMENDATIONS

1. Test Assembly

No particular problems are expected to be encountered in the detailed design and construction of the test system. The delivery time of equipment is in the range normally required for process equipment, but serious delays could occur if the fabrication and assembly of the tester were to be attempted by a company that has not had rather extensive experience with all the proposed propellants.

2. Analytical Instrumentation

The analytical techniques recommended for on-stream analysis of liquid or gaseous samples involve colorimetry, density, viscosity, gas chromatography, water analysis, nondispersive photometry, particle-size analysis, refractometry, use of specific electrodes (where applicable), and turbidity. When funding considerations are not critical, the following techniques could be used advantageously: activation analysis, mass spectrometry, microwave spectroscopy, rapid-scanning spectrophotometry, and X-ray fluorescence spectrometry.

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Figure 1

Figure 2

Figure 3

ISOKINETIC SAMPLING ASSEMBLY
SK0656-01-107
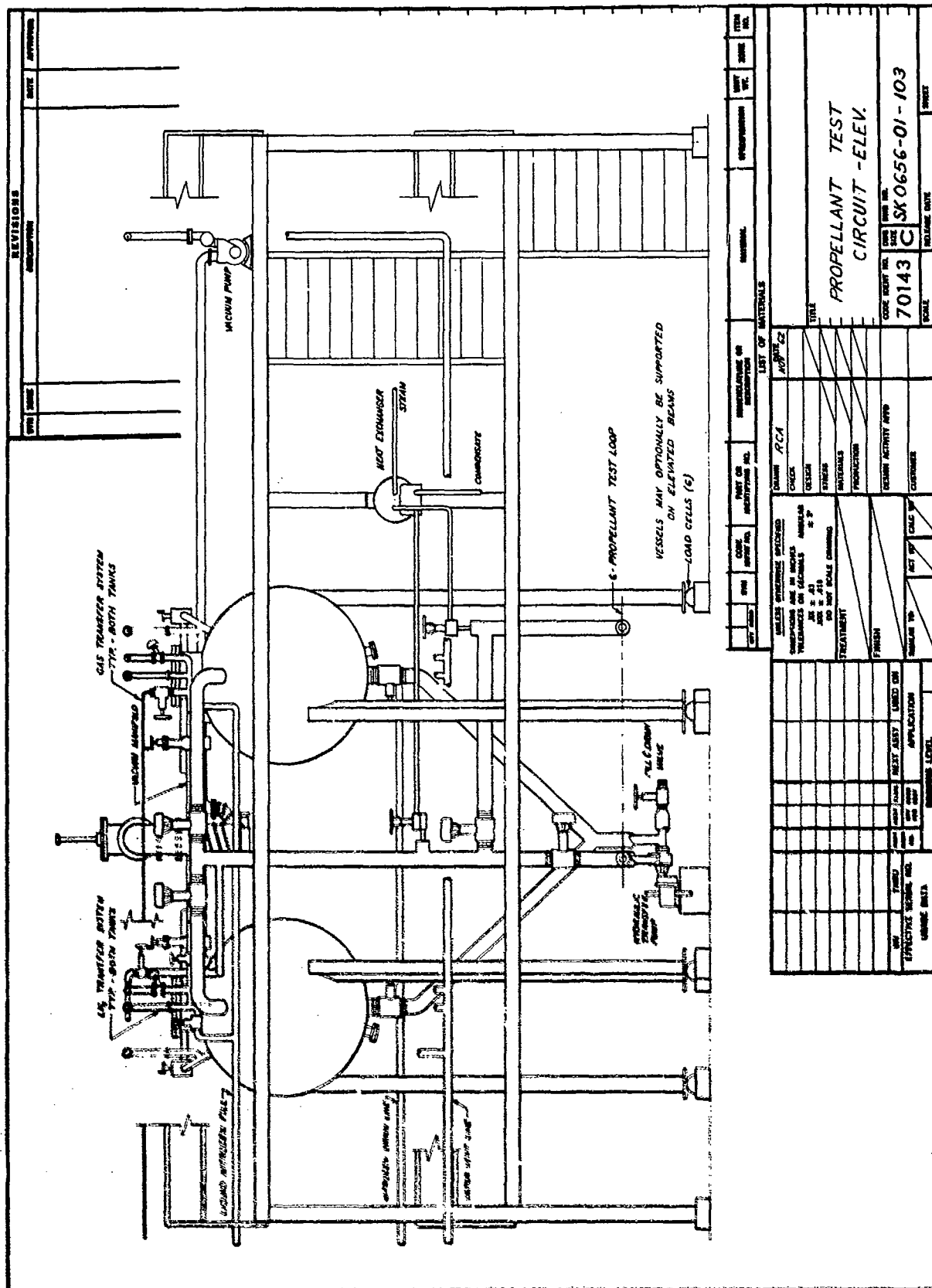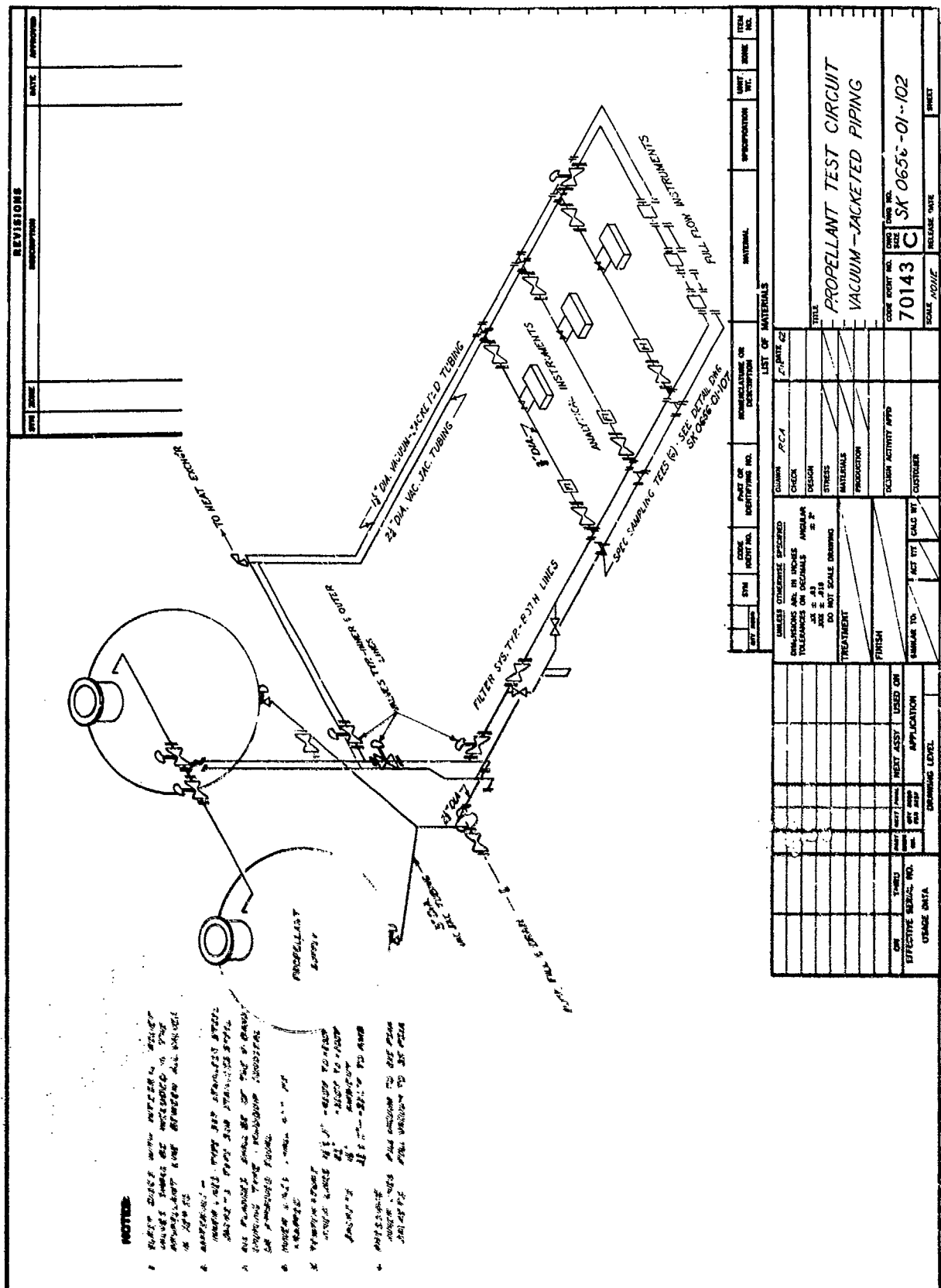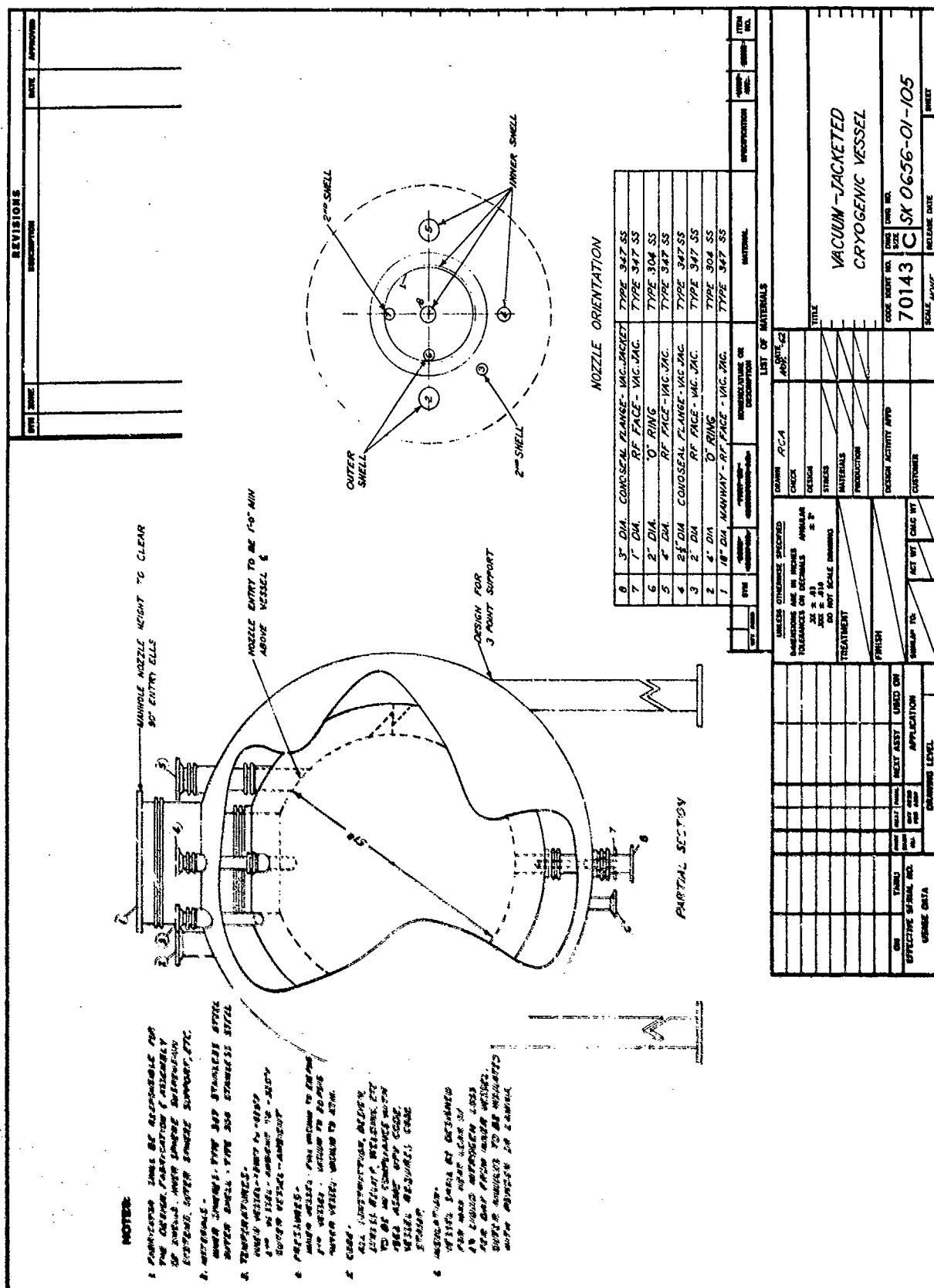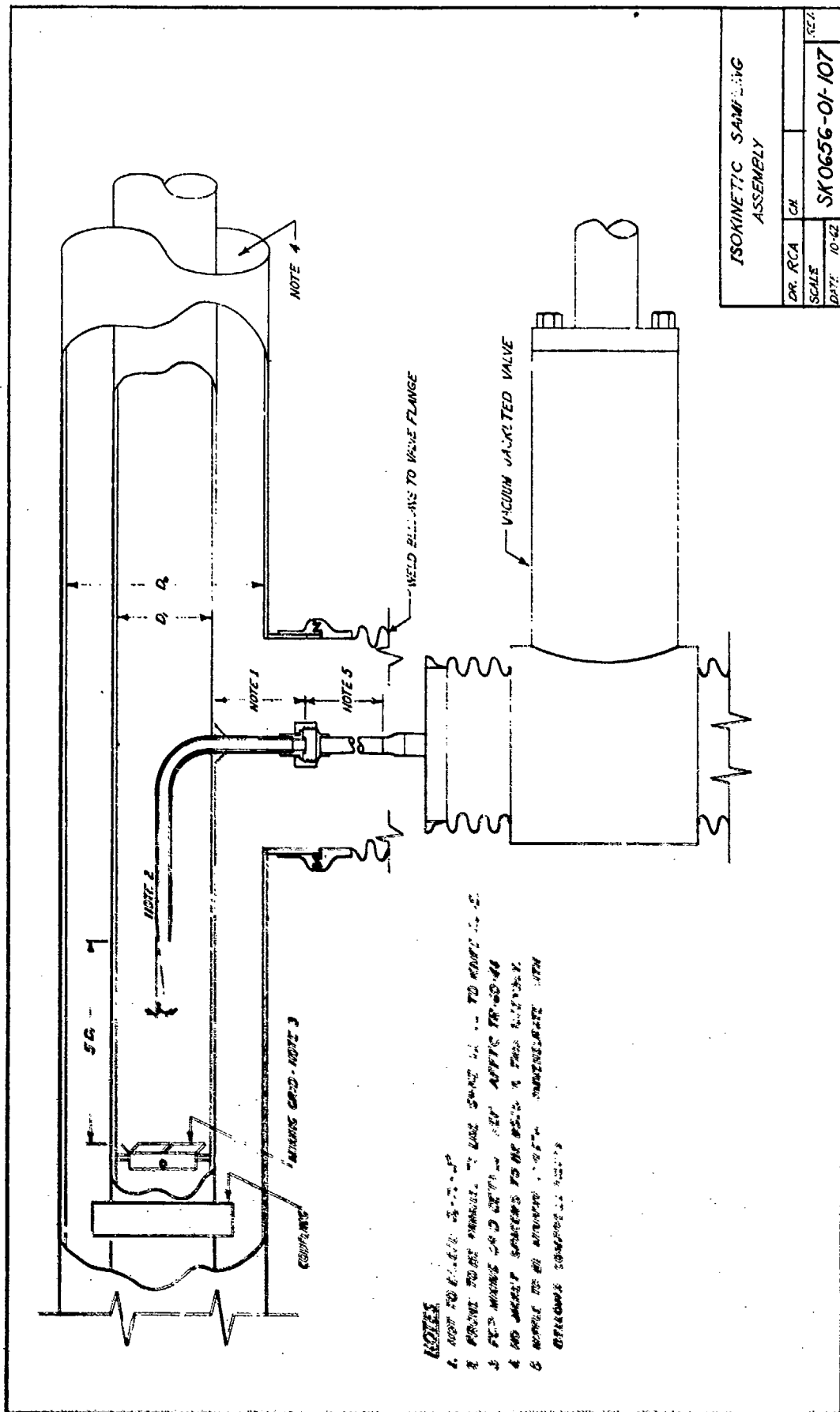
Figure 4

TABLE 1

FLOW CONDITIONS, IRON OXIDE CONTAMINANT*

Propellant	5-gpm Flow V fps	5-gpm Flow Re x 10^-4	Laminar Suspension Q gpm	Laminar Suspension V fps	Laminar Suspension Re x 10^-4	Turbulent Suspension Q gpm	Turbulent Suspension V fps	Turbulent Suspension Re x 10^-4	150-gpm Flow V fps	150-gpm Flow Re x 10^-4	150-gpm Flow ΔP psi
					2-Inch-Diameter Flow Line						
F_2	0.611	6.36	14.0	1.71	17.85	63.8	7.80	81.1	18.34	191	97.7
ClF_3		3.80	12.8	1.56	9.70	42.2	5.15	32.0		114	137
H_2O_2		1.04	13.1	1.60	2.73	25.9	3.17	54.3		31.4	125
B_5H_9		1.78	19.34	2.36	6.87	82.5	10.1	29.3		53.4	56.9
N_2O_4		3.01	14.1	1.73	8.50	43.1	5.28	26.0		90.2	113
					2.5-Inch-Diameter Flow Line						
F_2	0.375	4.98	24.4	1.79	–	144.0	10.8	–	11.33	151	36.2
ClF_3		2.97	21.9	1.64	–	83.3	6.25	–		89.6	48.8
H_2O_2		0.82	22.4	1.68	–	46.7	3.50	–		24.7	47.5
B_5H_9		1.39	33.1	2.48	–	155.0	11.6	–		42.0	19.2
N_2O_4		2.35	24.1	1.81	–	91.0	6.82	–		71.1	39.7

*Symbols: V, flow velocity; Re, Reynolds number; Q, volumetric flow rate; and ΔP, pressure differential.

Table 1

TABLE 2

MATERIAL COMPATIBILITY*

Propellant	Materials of Construction		Valves	Gaskets	Lubricants	Preferred Mode of Transfer
	Metals	Nonmetals				
Chlorine trifluoride	300-series SS; nickel; Monel; low-carbon, high-nickel steels; Inconel	Kel-F, Teflon, Pyrex	Braided-copper packing backed by Teflon rings, or shaped packing of Kel-F or Teflon	Teflon laminated with soft copper, 2S aluminum, sterling silver	Use of standard-based lubricants is prohibited; fluorocarbons form detonable mixture; none completely satisfactory	Standard pumps having a stuffing box not suitable, but diaphragm pumps, such as Lapp Pulsafeeder, may be used
Liquid fluorine	Monel, aluminum, Types 304L and 347 SS, copper, brass	None	Packless-type valves of SS, Monel, aluminum	Aluminum, tin, copper, gold	No reliable lubricants	Usually transferred by pressure differential between product chamber and atmospheric pressure; if pump is used, extreme caution is needed in design of shaft seal; mechanical seal, bellows or spring-loaded, incorporated in a positive-shaft-seal design
Nitrogen tetroxide	0.1% moisture or less: carbon steels, aluminum, SS, nickel, Inconel; wet: 300-series SS	Ceramic, Pyrex, Teflon, Kel-F, asbestos (cotton-free), polyethylene	Plug type with body and plug of Type 304 SS; body lines of aluminum-silicate-filled Teflon	Compatible nonmetals	Fluorolube series, Nordcoseal-147, DC 234S, water glass, graphite	Transfer by pump preferred; may be centrifugal or positive-displacement type, such as sealless Chempumps
Hydrazine and tetrafluoro-hydrazine	Mild steels, 300-series SS, 2S and 3S aluminum	Braided asbestos impregnated with Teflon, Teflon, high-density polyethylene, Garlock 735, Mylar film, unplasticized Kel-F	Solid Teflon cylinders, chevron rings, or braided Teflon equivalent to John Crane 704 or Garlock 5733 for valve systems	Teflon, polyethylene, spiral-wound 304 SS (Flexitallic)	None completely satisfactory, fair results with Quigley Co. Q-Seal	Conventional centrifugal pumps with graphite-impregnated asbestos or braided-Teflon packing satisfactory; sealless pumps can also be recommended because no shaft is involved
Liquid hydrogen	300-series SS; copper, bronze, brass, Monel, aluminum, Everdur	Dacron, Teflon, Kel-F, asbestos impregnated with Teflon, Mylar film, nylon	Gate or globe valves recommended, but plug or ball types may be used; must be capable of being purged efficiently and have adequate packing to provide good sealing and prevent clogging	Compatible materials	Not practical; vacuum grease satisfactory as a sealant with O-rings	Only pumps and shaft seals specifically designed and qualified by test for liquid H_2 shall be used for this service

*All information derived from Ref. 1.

Table 2 (Sheet 1)

TABLE 2 (cont.)

Propellant	Materials of Construction		Valves	Gaskets	Lubricants	Preferred Mode of Transfer
	Metals	Nonmetals				
Pentaborane	Iron, steel, Nickel, Inconel, SS, Inconel, Monel, Nickel, aluminum	Teflon, Kel-F	Plug valves with Teflon or Kel-F body liners; packless with metal diaphragm; globe valve	Teflon, Kel-F	Graphite	Pressurizing with an inert gas such as N_2 preferred; should pumping be necessary, either a diaphragm or magnetically driven pump should be used
Hydrogen peroxide	300-series SS (wrought) for less than 1 week, aluminum	Teflon, Kel-F	Modified (to ensure venting) gate and plug valve design should be such that H_2O_2 is not trapped in any part of valve; globe valves are approved, as are Y-type; a Teflon disk must be used to prevent metal-to-metal contact	Polyethylene, certain silicone rubbers, some polyvinyl chloride plastics, Kel-F, Teflon, pure tin or aluminum, Flexitallic	--	Pumps manufactured from 300-series SS or aluminum alloys 32 or 355 with 300-series SS shaft; suction chamber must be used to self-prime; must be sealed with mechanical seal or packed with braided or shredded Teflon, Kel-F, shredded aluminum, pure tin; chevron-type Teflon seal is good

Table 2 (Sheet 2)

TABLE 3

FLOW INDICATORS

Principle of Operation	Advantages	Disadvantages	Typical Manufacturers[*]
Sharp-edged orifice	Simple, cheap, accurate	High energy loss, narrow flow range	23, 6, 24
Venturi tube	Low energy loss, accurate	Narrow flow range, viscosity-sensitive	25, 26, 27
Positive-displacement meter	Direct reading, accurate for liquids, integrating	Expensive, requires bearings and seals subject to corrosion, difficult to transmit or control	28, 29, 30
Rotameters	Relatively wide flow range, simple, direct	Cannot use glass, difficult to record	31, 32, 17
Mass-flow meters	Measures mass flow, high accuracy	Expensive, complicated, shock-sensitive	33, 34, 17
Radioactive-particle counter	No moving parts, no connections	Expensive, radiation hazard, difficult to adapt to all different propellants	16
Turbine or velocity meter	Simple, high accuracy, wide flow range, versatile	Expensive	34, 35, 36, 37

[*]See Section A of Table 30 for names and addresses.

Table 3

TABLE 4

LIQUID-LEVEL INDICATORS

Principle of Operation	Advantages	Disadvantages	Typical Manufacturers[*]
Sight glass or gage glass	Direct visual level indication, simple	Fluorine attacks glass, impractical for cryogenics	1, 2, 3, 4
Floats	Direct, accurate, dependable	Cumbersome, subject to vibration and agitation, not practical for liquid H_2	5, 6, 7, 8, 9, 10, 11
Inductance, capacitance, magnetic	Indirect contact with fluids, easily transmitted	Not direct reading, requires calibration for each fluid	12, 13
X-ray or gamma ray	No contact with fluids, easily transmitted	Not direct reading, difficult to mount on large multiwalled tank	14, 15, 16
Gas bubbling	Simple, accurate, direct reading	Requires gas source, gas dissolves in liquid, subject to clogging and gas-flow stoppage	17, 9
Differential-pressure measurement	Accurate, easily transmitted, no flows, no packing glands	Requires connections to tank or vessel	18, 9, 19
Weight	Accurate, direct, no connections to tank	May be cumbersome, expensive	20, 21, 22

[*]See Section A of Table 30 for names and addresses.

Table 4

TABLE 5

NEUTRON SOURCES

	Pu-Be	Ra-Be	Sb-Be	Po-Be
Neutron output, n/sec/curie	1.6×10^6	1.5×10^7	1.1×10^6	2×10^6
Cost, $/curie	140	20,000	50	75
Cost/10^7 n/sec, $	880	13,500	450	375
Source half-life	24,300 years	1620 years	60 days	140 days
Comments	10 curies maximum	Expensive	Intense γ output, requires 9-in. lead shield, reactivation costs about $2000	No γ output, activity not renewable

Table 5

TABLE 6

NEUTRON GENERATORS

	Picker 2920	Texas Nuclear 9501	Phillips	High Voltage Engineering ANS 2000
Thermal-neutron output, n/sec	~10^6	4×10^8	~3×10^6	6×10^8
Fast-neutron output, n/sec	10^8	4×10^{10}	3×10^8	6×10^{10}
Pulsed operation	No	Yes	Yes	Yes
Pulse duration, microsec	NA*	1 to 10,000	10 to 500	10 to 200
Neutron energy level, Mev	14.3	14.3	14.3	14.3
Generator type	Van de Graaff	Cockcroft-Walton	High-voltage transformer	Van de Graaff
Accelerating voltage, kv	130	150	125	500 to 1000
AEC license required	Yes	Yes	Yes	Yes
Tube life, hours	500	-	200 to 400	1000, or 1 year
Maintenance	Replace Van de Graaff belt	Periodic cleaning of Vacion pump	Replace tritium periodically	Replace Van de Graaff belt
Cost of shielding, $	-	2000	2000	5000

* Not applicable.

Table 6 (Sheet 1)

TABLE 6 (cont.)

	Picker 2920	Texas Nuclear 9501	Phillips	High Voltage Engineering ANS 2000
Space required, ft	Howitzer (2 ft in dia x 4 ft long)	10 x 10	-	15 x 32
Utilities	110 v, 60 cps, 250 watts	110 v, 60 cps, 30 amp	220 v, 30 amp	110 v, 60 cps, 3-phase, 4-wire
Cost, $	3000	24,500	15,000	Basic, 38,500; pulsing, +2,500
Exposure	◄——— Proper shielding, 40 hours/week ———►			Dosage: 100 mr per 20-hour week
Remote cable, ft	20	33	31	25-ft standard up to 150 ft
Comments	Belt replacement takes 10 to 15 min; counting equipment, 3-in. crystal, $3000	Complete facility in near future for $40,000 to $50,000	Tritium replacement takes about 2 hours and costs about $1500	Complete facility costs about $50,000; cooling water, liquid N_2, Dry Ice required

Table 6 (Sheet 2)

TABLE 7

PARTICLE-SIZE ANALYZERS

	Sperry Products 50 C 494	High Accuracy Products	Rayco Model 300	Phoenix Precision
Sample flow	0.1 gpm, max	1 to 10 cc/min	400 cc/min, max	-
Sample-line diameter, in.	2 or 3	1/2	5/16	1/4
Sample temperature	To 100°C	To 200°F	40 to 150°F	-
Sample pressure	To 3000 psi	To 250 psi	To 500 psi (special)	-
Sample disposition	Returned	5 to 10 cc lost, remainder returned	Returned	Returned
Materials contacting sample	Line + transducer + epoxy	Stainless steel, glass, epoxy	inless steel and quartz (special)	-
Unit explosion proof	No	Not normally	Available	-
Recorder	Not included in price	Available: Hewlett-Packard 560 A (digital)	Available: 100 mv	Available: 5 mv, dc
Instrument size, in.	16 x 24 x 30	22 x 30 x 18	24 x 37 x 25	-
Power requirements	110 v, 60 cps, 750 watts	110 v, 60 cps, 6-amp fuse	110 v, 60 cps, 900 watts	-
Response time	0.1 sec	Determined by sampling	-	-
Particle-size range, microns	>25	5 to 2500 in 5 steps	3 to 100 in 15 steps	-

Table 7 (Sheet 1)

TABLE 7 (cont.)

	Sperry Products 50 C 494	High Accuracy Products	Royco Model 300	Phoenix Precision
Accuracy	±0.1% in counts	±0.1%	-	-
Maximum counting rate	4000 cps	10,000 cpm	30,000 cpm	-
Maximum count	1,000,000	100,000	100,000	-
Counting time	2 to 30 sec	Minimum of 30 counts	0.3, 1, 3, or 10 min	-
Price, $	9840	6000	9350	-
Problem areas	Transducer in sample	5 microcells required to cover 5 to 2500 micron range; cost, $800 per microcell	Counts one size range at a time; can add channels for counting additional size ranges at $1200 per channel	Primarily a laboratory instrument

Table 7 (Sheet 2)

	Unilectron NKS-021	Electro-Optical KFC-600	Fairchild		Bell & Howell	Re... WF2
			HS 108	HS 401		
Type	Kerr cell	Kerr cell camera	Camera 8-sided prism	Camera 4-sided prism	Framing camera	Camera 8-sided
Speed, pps (effective)	--	100,000,000	7000 to 14,000	To 8000 at 60 v	200 (35 mm) 128 (16 mm)	700 to 18
Exposure time	5 to 100 nanosec	5 nanosec to 5 microsec	--	--	--	--
Film capacity or total exposure	NA*	6 frames	100 ft	400 ft	--	400 ft
Focal lengths	NA	12 in., f/3.3	76 mm, f/1.9	5 to 152 mm, f/1.5 to f/4.0	--	50 mm, f/
Aperture	Effective: 2 in. dia	0.80 by 1.50 in.	Adjustable for 8 mm or split 16 mm	16-mm camera	--	Interchan 0.005 to (in. by 0.1 in.
Utilities and power	60 kv, dc	Operating voltage, 35 kv	--	--	--	--
Price, $	4550 Kerr cell plus pulse generator	20,000, complete camera	--	3000, choice of 1 motor, 1 lens	--	2775
Comments	Power supply, $710; custom schlieren, $12,000+; custom shadowgraph, $1000+; weight, 25 lb	Interframe time, 5 nanosec to 25 microsec; KSC-10, $5950	Weight, 14 lb; HS 408, $9520 (400 ft of film); power supply required; lighting extra; speed range depends on motor	Speed range depends on motor; HS 101, $1650; lighting extra	--	Weight, 35 8-mm film; lighting s power supp extra; Wollensak 32 models

TABLE 8

HIGH-SPEED PHOTOGRAPHIC EQUIPMENT

Fairchild		Bell & Howell	Revere Wollensak		Beckman & Whitle...		
HS 108	HS 401		WF2	WF6	Model 200	Model 189	Magnifa...
Camera 6-sided prism	Camera 4-sided prism	Framing camera	Camera 8-sided prism*	Oscillographic	Streak and framing camera*	Framing camera	High-speed motion-pic camera
7000 to 14,000	To 8000 at 60 v	200 (35 mm) 128 (16 mm)	700 to 18,000·	--	Framing, 550,000	Model 18000B, 48,000 to 4,300,000	200 to 320
--	--	--	--	4 to 100 ft/sec	Streak, 18 microsec; framing, 12.7 microsec	--	--
100 ft	400 ft	--	400 ft	100 ft	Streak, to 6.9 mm/microsec	25 frames, 100 ft	16-mm film
?? mm. f/1.9	5 to 152 mm, f/1.5 to f/4.0	--	50 mm, f/2.0	50 mm, f/2.0	f/10 max	24 in., f/14.5	50 mm, f/1...
Adjustable for 8 mm or split 16 mm	16-mm camera	--	Interchangeable 0.003 to 0.040 in. by 0.410 in.	--	Framing, f/10.0; streak, f/6.5	f/14.5	f/1.9
--	--	--	--	8 to 280 v, dc	--	--	115 v, ac or dc
--	3000, choice of 1 motor, 1 lens	--	2775	1570	19,550	40,500	1995, Model 333
Weight, 14 lb; HS 408, $5520 (400 ft of film); power supply required; lighting extra; speed range depends on motor	Speed range depends on motor; HS 101, $1650; lighting extra	--	Weight, 38 lb; 8-mm film; lighting and power supplies extra; Wollensak has 32 models	Lighting and power supplies extra	Automatic controls, installation included, lighting extra	35-mm perforated film	--

2

	Beckman & Whitley				Photo-Sonics 1C	Edgerton, Germeshausen & Grier	General Metallic
	Model 200	Model 189	Magnifax	Dynafax			
graphic	Streak and framing camera	Framing camera	High-speed motion-picture camera	Continuous-writing, framing camera	Rotary-prism recording camera	Model FX-6A xenon flash tube	High-speed drum camera
	Framing, 550,000	Model 18000B, 48,000 to 4,300,000	200 to 3200	200 to 26,000	To 4000	To 1000	--
	Streak, 18 microsec; framing, 12.7 microsec	--	--	39 microsec at top speed	--	--	--
	Streak, to 6.9 mm/ microsec	25 frames, 100 ft	16-mm film	33-7/8 in., 8.62 millisec at top speed	400 ft, 16 mm	NA	9 in. max, 160 mm/ millisec
	f/10 max	24 in., f/14.5	50 mm, f/1.9	3 in., f/2.8	--	NA	150 mm, f/2.8
	Framing, f/10.0; streak, f/6.5	f/14.5	f/1.9	f/2.8	--	NA	--
	--	--	115 v, ac or dc	120 v, ac	--	To 650 v	Air, 0.07 lb/sec at 90 psig
	19,550	40,500	1995, Model 333	89,000	5500	15	2900
d les	Automatic controls, installation included, lighting extra	35-mm perforated film	--	For events moving at 10 to 200 meters/sec, unity magnification; films: Kodak Tri X neg, Du Pont Superior 4, Ilford HP3	Magazines to 1200 ft	14,000 peak candle power, to 5 watt-sec/flash, FX-12 goes to 6000 pps, $35	Focal length, 4 ft to infinity; field of view, 18°

3

Table 8

TABLE 9

WATER ANALYZ...

	Beckman Consolidated MEECO	Consolidated Model 26-312	Westberg	Qualicon 507-2	Mine Safety Water Vapor Recorder	Boonton Polytech Model 10
State of sample	Gas	Liquid	Penetrable solid or liquid	Liquid	Gas	Liquid
Principle of operation	Coulometric	Coulometric	Conductivity	Gamma reflection	Heat of absorption	R-F power absorption
Range of water	0-10 to 0-1000 ppm	0-10 to 0-1000 ppm	Depends on use, to 30%	2 to 30%	0-10 to 0-5000 ppm	0 to 80%
Continuous or batch	Continuous	Continuous	Standard use, batch	Continuous	Nearly continuous	Continuous manual
Applications	Cryogenics	Unreactive organics	With flow cell, storables	Hydrogen-free propellants	Vaporized cryogenics	--
Interferences	Corrosives, oxidizable polymerizables	--	Other conductive impurities	Hydrogen compounds	Corrosive or adsorbed compounds	--
Flow	100 cc/min	Depends on water content	NA*	0 and up, depends on line	9 liters/min	--
Temperature	Ambient	To about 200°C	--	0 to 200°F	Controlled	Compensa... available
Pressure, psi	10 to 100	10 to 100	NA	Determined by sample line	10, min	--
Materials in contact	SS, Pt, P_2O_5, Teflon	303, 316 SS, high-Ni alloy, cell	--	Sample line	Adsorbent, et al.	--
Response time	63% in 90 sec	63% in 90 sec	--	Variable, approx 10 sec	4-min cycle	1 to 2 s...
Output to recorder	0-10 to 0-50 mv	0-10 to 0-100 mv, dc	--	0 to 10 mv	Recorder provided	0 to 50 ...
Utilities	110 v, 60 cps	110 v, 60 cps, 35 watts	Dry cell	110 v, 60 cps	110 v, 60 cps, 200 watts	115 v, 60 cps, 200 watts
Price, $	675 to 725	2850	75	30,500	6000 to 7000	--
Comments	--	Sample must not have high viscosity; inert stripping gas required	Standard instrument is portable, with meter indication; could easily be used for continuous measurement	Density must also be determined	Only water should be adsorbed	Moisture gradients do not affect analysis
Accuracy, %	5	10	--	2	1% of full scale	0.5

*Not applicable.

TABLE 9

WATER ANALYZERS

Mine Safety Water Vapor Recorder	Boonton Polytechnic Model 100	Moisture Register	American Meter Diacon	Burrows	Foxboro Dynalog	Instruments Model C	Robertshaw Microsen
Gas	Liquid	Solid and powder	Liquid or gas	Solid	Liquid	Liquid	Liquid
Heat of absorption	R-F power absorption	R-F power absorption	Capacitance, 15 kc	Capacitance	Capacitance, 1.6 mc	Capacitance, 3.5 mc	Capacitance, 500 kc
0-10 to 0-5000 ppm	0 to 80%	Adjustable	Adjustable, 0 to 30 ppm and up	4 to 35%	Capacitance, 2 to 200 μμf	0 to 35%	Capacitance, 10 to 500 μμf
Nearly continuous	Continuous, manual	Batch	Continuous	Batch	Continuous	Continuous	Continuous
Vaporized cryogenics	--	--	Essentially unlimited (BS&W)	Designed for cereal grains	Liquid Cl_2 and others	Petroleum and others	Designed for liquid-level measurement
Corrosive or adsorbed compounds	--	--	Other high-dielectric materials	←——— High-dielectric materials ———→			--
9 liters/min	--	NA	As required	NA	As required	As required	As required
Controlled	Compensation available	--	Compensated	Ambient	Compensated, -20 to +140°F	Compensation, 10 to 165°F, available	To 350°F
to, min	--	NA	To 1000	NA	To 150	Depends on cell	To 500
Adsorbent, et al.	--	--	SS, desiccant	--	316 SS, Teflon	No. 40 steel	SS, Teflon
4-min cycle	1 to 2 sec	1 min/test	30 sec	--	--	--	--
Recorder provided	0 to 50 mv	--	0 to 10 mv, or 0 to 100 microamp	--	2 to 200 μμf	4.5 to 1100 μμf	10 to 500 μμf
110 v, 60 cps, 200 watts	115 v, 60 cps, 300 watts	110 v, 60 cps, 10 watts	115 v, 60 cps	--	115 v, 60 cps, 75 watts	110 v, 60 cps	110 v, 60 cps
6000 to 7000	--	445	1800	545	750	890	750
Only water should be adsorbed	Moisture gradients do not affect analysis	Solids must be pressed; moisture gradients do not interfere	Recorder extra; takes side stream 3/4-in. pipe; particularly good for low moisture levels	Printed circuit cards for various grain characteristics	Temp comp, $869; 2-in. flow cell, $579; cell constants of 5.2, 14.3, 21.5, and 28 available	Flow cell: 2-in. NPT connection	Price includes 10-in. circular chart
1% of scale	0.5	--	2	--	1	0.5	--

2

TABLE 10

SPECIAL ELECTRODES

	19521 Beckman Chloride	19501 Beckman pH	L&N pH (7764)	778 Beckman Dissolved O_2
Temperature	100°C	-5 to 100°C	To 90°C	To 80°F
Pressure, psig	~100 (psi)	To 100	To 100	To 2
Connection, in.	1/2, 1	1/2, 1	1	1/2
Insertion, in.	1/2	1-1/2	5	Flush
Price, $	56	25	1917	450
Comments	Fits in flow chambers, cannot use all-metal flow chamber	Fits in flow chamber; No. 72500 is SS, $200; electrodes: No. 19500 $25, No. 19505 (high Na) $25	Flow unit, $228; compensator, $44; glass electrode, $24.50; recorder, 1596; filtration needed; calomel reference, $24.50	Fits in flow chamber; electrode, amplifier, and control box included; contact with SS, Teflon, Viton A; gas or liquid streams; O_2 reduced to H_2O

Table 10

TABLE 11

OXYGEN MONITORS

	Beckman F3	L&N 7803-F-1	Analytic Systems Series 308	Beckman Model 80	Greenbrier Series 300	MSA Type C-4
Oxygen range	0 to 5%, 0 to 25%	0 to 5%, 0 to 10%	0 to 10 ppm, 0 to 1%	0 to 5 ppm	0 to 10 ppm, 0 to 5000 ppm	0 to 1%, 0 to 35%
Accuracy, %	1	1.5	2	5	2	2
Response time, % in sec	90 in 40	90 in 30	90 in 60	95 in 120	90 in 30	90 in 15
Readout	0 to 5 mv	-	0 to 5 mv	0 to 5 mv	Recorder	Meter
Principle	Paramagnetism	Paramagnetism	Galvanic	Galvanic	Galvanic	Galvanic
Sample flow, cc/min	50 to 250	-	150 to 300	100	50	75
Price, $	1530	1455	Explosion proof, 2450	2080	2000	1200
Comments	Sample pressure, 0 to 20 psi; sample temp, 50 to 100°F; G-2, $2650	-	Sample at 1 to 150 psig, 60 to 100°F	Sample at 2 to 30 psig	Recorder extra	Multiple line sampling possible

Table 11

TABLE 12

ROBOT CHEMISTS

	Hagan Chemonitors	Milton Roy		Research Specialties Model AT 7600	Technicon
		Chemalyzer	Quantichem		
Line diameter, in.	1/4	1/4 OD plastic	1/4 tubing	NA*	-
Sample required	5 ml/min	22 ml/anal.	Function of contaminant level	Takes aliquots	Approx 0.3 ml/anal.
Sample flow	75 ml/min	Minimum, 2.5 gph	1 liter/min, max; 10 gph, av	NA*	-
Sample pressure	To 100 psi	To maintain flow	15 to 20 psig	NA	-
Sample temperature, °F	To 120	Ambient	60 to 100	Ambient	-
Operations performed	Add reagent, mix, measure	Meter 1 reagent, mix, measure	Add up to 4 reagents	Pipets and titrates	Measure, mix, dialyze, heat
End point or analysis performed	Colorimetric, conductivity, electrometric	Colorimetric	Colorimetric	Electrometric	Colorimetric, flame photometric
Number of streams	1	1	To 4	NA	1 to 16
Number of components	Electrometric: titrates to 2 end points	1	1	Multiple-end-point possibility	4
Time per analysis or number per hour	Standard: 5-1/2 min/anal. (3 to 7-1/2 min/anal.)	3- or 6-min cycles	6 to 15 min/anal.	60 anal./hour	4 min/anal., to 240 anal./day
Record, recorder	Pow?g (0 to 100 mv) recorder	Meter provided; recorder, 0 to 50 mv	Single-point or multiple-point recorder	Digital printout or chart	
Power required	110 v, 60 cps, 250 to 300 watts	115 v, 60 cps, 0.45 amp	115 v, 60 cps, 150 watts	115 v, 60 cps, 750 watts	
Materials in contact	Tygon, glass, SS	Plastic or glass	Plastic or glass	Glass, Teflon	

* Not applicable.

Table 12 (Sheet 1)

TABLE 12 (cont.)

Parameter Characteristics	Milton Roy		Research Specialties Model AA 7500	Technicon
	Chemalyzer	Quantichem		
Reagent consumption	Approx 0.5 ml/min	Approx 0.7 ml/anal.	Approx 400 ml/day	Approx 10 ml/anal.
Color (wavelength)	Color filters	4 color filters (415 to 700 millimicrons)	As required	Et
Colorimeter, cell path	5 or 20 mm	2 to 5 cm	2 to 5 cm	40-ml filtration cell
Price, $	1 point, 8500; 4 point, 9500	1213	Basic, 5500	Digital, 7950; recorder, 525
Comments	Conductivity ranges from 0-10 to 0-100,000 micromhos	—	Also requires air at 20 psi	Also requires distilled-water source

Table 12 (Sheet 2)

TABLE 13

FLAME PHOTOMETERS

	Technicon Autoanalyzer	Waters Associates Model 103
Sample required	As little as 0.3 ml/anal.	Approx 5 ml/min
Sample flow	Sample cups loaded onto sampler plate	10 to 100 cc/min
Line connection	NA*	1/4 in.
Sample disposition	NA	Some used, some discarded
Sample temperature	Ambient	50 to 110°F
Sample pressure	Atmospheric	Slightly above atmospheric
Range of concentrations	-	Typical: sodium, 0-10 or 0-100 ppb
Accuracy	-	1-1/2% of full scale
Response time	-	90% in 30 sec
Readout	-	Strip-chart recorder
Recorder	-	Provided
Materials in contact	-	SS
Hazards	-	Fire or explosion under some circumstances
Safety devices	-	Flameout circuit shuts off O_2 and H_2
Utilities	-	115 v, 60 cps, 300 watts
Maintenance	-	1 hour/month for cleaning of burner
Flame type	Oxygen-propane	Oxygen-hydrogen or oxygen-air
Warmup time	-	1 hour
Price	-	$10,000 for single point
Comments	Manual loading of sample cups	$12,500 for 5-point unit

*Not applicable.

Table 13

TABLE 14

X-RAY FLUORESCENCE SPECTROMETERS

	Applied Research Quantrol	General Electric Model XEG	Phillips Norelco
Number of elements	1	To 6	To 6
Range of elements	Ti to U	Ca to U in air or N_2, Al to Ca in He	Ti to U
Instrument temperature, $^\circ F$	45 to 90	40 to 110	Ambient
Sample presenter	Continuous-flow cell	Powder: 8 cu in./min at 15 in./min	Flow cell for liquids
Sample disposition	Returned	Nondestructive sample returned	Returned
Remote location, ft	To 300	25	-
Response time	Depends on sensitivity required	Time constants available: 1, 5, 10, 30, and 60 sec	Essentially instantaneous
Range of concentrations	◄─────────── Approx 1 to 100% ───────────►		
Accuracy	1% (precision, 1%)	Depends on chemical analysis for standardization	-
Readout	◄─────────── Recorder ───────────►		
Recorder	Ratio recording	Available: strip chart, circular chart, printers, etc.	Provided

Table 14 (Sheet 1)

TABLE 14 (cont.)

	Applied Research Quantrol	General Electric Model XEG	Philips Norelco
Materials in contact	Sample presenter only (e.g., Teflon and Mylar)	Sample presenter only	Teflon flow cell with Mylar window
Explosion proof	Not required on unit head	No	Available
Hazards	Nil	<0.25 mr/hour	None during normal operation
Safety devices	Safety-interlock circuitry	Fail-safe device for cooling, window breakage	Built in
Maintenance	No periodic maintenance	No periodic maintenance	Flow-cell change, 50 sec
Utilities	230 v, 50/60 cps, single-phase	230 v, 60 cps, 30 amp, single-phase	220 v, 20-amp fuse
Price, $	30,000 (single stream)	40,000 to 80,000	20,000 (1 stream, 1 component)
Comments	Cooling water, 1 gpm; dispersive or nondispersive detector system; up to 24 streams; Model 25000 VXQ, to 9 elements; Model 20650 VPXQ, to 22 elements	Cooling water, 5 gpm; helium, 1 cfh; other sample presenters quoted as required by application	About the size of a large desk; cost includes application engineering, construction, installation, 12-month service contract; instrument capable of 1 to 6 elements in 1 to 15 streams; monitors liquids, slurries, powders, solids

Table 14 (Sheet 2)

TABLE 15

POLARIMETERS

	Bendix Type 143A Automatic Polarimeter
Line diameter, in.	1/4 or 3/8 Tygon
Flow rate	0 and up
Sample temperature, $^\circ$F	Ambient to 200
Temperature variation	Control or compensation not provided
Filtration	Required, available as option
Sample disposition	Returned
Materials in contact	SS, glass, Tygon
Recorder	Available, $695
Explosion proof	Probably not
Range of measurement	$\pm 0.1^\circ$ of arc from preset "zero"
Accuracy	1 part in 2500
Sensitivity	$\pm 0.0002^\circ$ of arc
Response time	10 sec to $\pm 0.001^\circ$ of arc 30 sec to $\pm 0.0003^\circ$ of arc
Cells available	5, 10, 20, or 30-mm path
Power requirements	110 v, 60 cps, 1.2 amp
Price	$3710
Comments	Incandescent light source, use filters to obtain specific wavelengths, digital readout available

Table 15

TABLE 16

REFRACTOMETERS

	Barnes RE-A4	MSA	Optics Technology Model 500B	Waters In-Line	Daystrom Indexometer
Line diameter, in.	1/8 or 1/4	1/4	1	1/4 to 4	To 8
Sample flow	0. to 0.25 gpm	5 to 20 cc/min	Not critical	Not critical	Not critical
Sample temperature, °F	To 250	To about 200	To 212	To 300	32 to 212
Temperature variation	Control	Control	Compensated	Compensated	Compensated
Sample pressure	To 150 psi, 20 to 50 psi desirable	Low	--	Vacuum to 250 psig	Vacuum to 150 psi
Filtration	Recommended	Required	Not required	Not required	Not required
Sample disposition	←	Returned	→		
Materials in contact	Glass and SS	SS and prism (quartz)	SS and dielectric rod	SS (316, 303, or 304), prism	SS and prism
Explosion proof	Available, Class I, Group D	Yes	--	Yes	Available, Class I, Group D
Recorder	Available	Available, 0 to 100 mv	Available, 0 to 10 mv, dc into 50C ohms	Available, 0 to 100 mv	Available

Table 16 (Sheet 1)

TABLE 16 (cont.)

	Barnes RE-A4	MSA	Optics Technology Model 500B	Waters In-Line	Daystrom Indexometer
Range	0.01 standard	Custom to 0.005 RI	1.333 to 1.490	0.005 to 0.1 RI (see comments)	1.30 to 1.65
Sensitivity	To 0.000002 RI	0.0005 max	0.0002 RI	0.25% of scale; accuracy, 1% of scale	0.005 RI max
Response time	15 sec	90% in 15 to 30 sec	<1 sec	90% in 20 sec	4 millisec
Power required	115 v, 60 cps, 200 watts	110 v, 50/60 cps, 100 watts	110 v, 60 cps	110 v, 60 cps, 60 watts	110 v, 50/60 cps
Price, $	5200	3800	2350	3000	5000
Comments	-	Non-explosion-proof model, $3000	Dielectric rod is glass	Range depends on RI of prism as follows: 1.23 to 1.38, fused quartz; 1.30 to 1.48, glass; 1.43 to 1.64, spinel	Prism: quartz is standard, sapphire probably available

Works for turbulent, opaque, or colored solutions containing suspended solids

Table 16 (Sheet 2)

TABLE 17

COLORIMETERS

	Hallikainen Model 1274	Beckman Model 77	Photovolt Model 400-S
Line diameter, in.	1/2	3/4	3/4
Flow rate	100 ml/min recommended	Liquid, to 5 gpm; gas, to 3 cfh	As required
Sample temperature, °F	To 150	0 to 300	Determined by system
Temperature control	Not required	None required	None provided, usually not required.
Sample pressure	To 50 lb	To 150 psig	Determined by system
Sample disposition	←——————————— Returned ———————————→		
Filtration	Not furnished, usually not required	Not required	Should be provided
Materials in contact	SS, cell windows	316 SS, cell windows	Flow tube
Wavelength range	Fixed at 1 wavelength in visible range	350 to 550 millimicrons, blue; 500 to 1000 millimicrons, red	Visible
Cell paths available	1/2 to 1 in. (approx)	1, 2, 5, 10, 25, 50, and 100 cm	1/2 to 2 in.
Cell windows	Glass	Glass	Pyrex
Range of instrument	As desired	0 to 50% T or 0 to 100% T	2 to 98% T

Table 17 (Sheet 1)

TABLE 17 (cont.)

	Hallikainen Model 1274	Beckman Model 77	Photovolt Model 400-S
Accuracy, %	-	2	2
Response time	4 to 5 sec, max	Determined by cell geometry	Approx 0.5 sec
Recorder	Available, 100 mv	Available, 0 to 10 mv or 0 to 100 mv	Available
Utilities	110 v, 60 cps	110 v, 60 cps, 75 watts	110 v, 50/60 cps
Explosion proof	Yes	Class I, Group D, Division 1	No
Price, $	600	2620, short path; 2670, 10 to 100-cm path	285
Comments	-	4-hour warmup, other windows available if needed	Cell is a flow tube, Pyrex

Table 17 (Sheet 2)

TABLE 18

NONDISPERSIVE PHOTOMETERS

	Analytic Systems				Hallikainen Model 1272	Du Po...
	Model 500	Model 600	Model 650	Model 700		
Wavelength range	Near infrared	Ultraviolet - visible	200 to 700 millimicrons	Infrared, depends on optics	Ultraviolet	210 to millin
Lamp sources	W filament	Hg, H$_2$, W	Hg, W	Nichrome at 600 to 700°C	Hg, standard	W, Hg
Sensitivity	To 0.02 A, full scale	To 0.02 A, full scale	To 0.1 A, full scale	To 0.02 A, full scale	--	Typic Abs to
Accuracy, %	1	1	5	1	--	2
Cell paths available	0.05 mm to 20 cm	Varied, 0.05 mm to 20 cm	0.05 mm to 50 cm	To 50 cm	--	0.00 (to 2
Windows available	Quartz (or glass or sapphire)	Quartz	Quartz	Na$_2$Cl, sapphire, CaF$_2$, AgCl, BaF$_2$, quartz, fused silica, Ge, et al.	--	Quartz
Types of samples	←			Liquids or gases		→
Line connection, in.	1/8	1/8	1/8	1/8	--	3/4 NP
Sample flow	50 to 100 cc/min	Liquids, to 30 cipm; gases, 30 to 60 cipm	50 to 100 cc/min	30 to 200 cipm	--	Depend and de respon
Sample temperature	Near ambient	40 to 110°F, or to 125°F	Ambient	50 to 100°F	--	0-200° or to
Sample pressure	To 450 psi	To 150 psi	A few pounds	To 100 psi	--	To 50 ard, o psig
Materials in contact	SS, cell windows	304 SS, quartz, Teflon	SS, Pyrex, cell windows	SS, cell windows	--	304 SS
Record	Signal only	Signal only	Meter	Signal only	--	Signal 1 v fu 20 mil
Recorder	Available, ratio recording	←	Potentiometer recorder (0 to 5 mv)	→	Available, 0 to 10 mv	Availa
Response time	30 sec	90% in 5 to 30 sec	Depends on flow rate	99% in 15 to 30 sec	1 sec	0.02
Explosion proof	←			Yes		→
Power required	115 v, 60 cps, 300 watts	115 v, 60 cps, 160 watts	115 v, 60 cps, 100 watts	115 v, 60 cps, 100 watts	115 v, 60 cps, 1 amp	6 to 60 cp
Remote-control unit	←		To 2000 ft		→	To 500 ft	To 100
Price, $	3500 to 4200	3500 to 4200	1500 to 1900	3000 to 4800	2300	3200
Comments	Cell pressure and temperature control available	--	No retaining feature as on others, to quicker resp	--	--	charge suppres availab

TABLE 18

ISPERSIVE PHOTOMETERS

	Hallikainen Model 1272	Du Pont Model 400	MSA Model 100	Beckman Model ??	Leeds & Northrup Model 6048
	Ultraviolet	210 to 650 millimicrons	Infrared	Infrared, to user's specification	2 to 14 microns, depends on optics
	Hg, standard	W, Hg, or Osram	Nichrome	Nichrome	--
	--	Typical: 0-0.5 Abs to 0-4.00 Abs	Typical: full scale 0 to 40 ppm CO_2, 0 to 2 ppm acetylene	To 0.1 ppm, depending on application	To 0.003%
	--	2	1	1	--
	--	0.005 to 7 in. (to 24 ft)	To 40 in.	Gas, 1/8 to 13-1/? in. standard; available, to 1 meter	1 to 9 in.
	--	Quartz standard	Sapphire, quartz, CaF_2, BaF_2, etc.	Quartz, sapphire, KRS-?, CaF_2, BaF_2, Irtrans	CaF_2, $BaCl$, $AgCl$, quartz, or others
	--			Liquids with high vapor pressure, or gases	bases
	--	3/4 NPT	1/4 or 3/8	1/4 Swagelok	1/4 or 3/8
	--	Depends on cell and desired response	Optimum, 3 lpm; range, 0.2 to 6 lpm	1 to 2 cfh	3 to ? cfh
	--	0-200°C standard, or to 350°C	-40 to +120°F	Very wide range of gases, no liquid cryogenics	? to ?? °F
	--	To 50 psig standard, or to 1000 psig	Available to 1000 psig	To 1500 psig	? ?
	--	304 SS, quartz	Au/SS cell, windows	Cell window ? for short-path gas	Al-glazed cell, cell window
	--	Signal adjustable 1 v full scale to 20 kilohms	Recorder	Recorder available	Strip chart or round chart
	Available, 0 to 10 mv	Available	Provided	0 to 100 mv	Provided
	1 sec	0.001 to 1 sec	90% in 25 sec	As fast as 90% in 5 sec	About 13 sec
			Available	Analysis units Class 1, Group ?	Yes
	115 v, 60 cps 1 amp	95 to 130 v, 60 cps, 500 watts	95 to 125 v, 60 cps, 800 watts	115 v, 50/60 cps, 135 watts	115 v, 60 cps, 300 watts
	To 500 ft	To 500 ft	To 4000 ft	50 ft standard, to 500 or 400 ft standard	To 100 ft
	3300	3000	3000	1/8-in. gas cell, $3500; 13-1/2-in. gas cell, $100?	?$$ with most of optionals
	--	Absorbance "zero suppression" available	Model 200, $1475; Model 300, $1385	Cells and windows easily removed for servicing; micrometer cell available for liquids	Needs dust filters and moisture trap

2

Table 18

TABLE 19

RAPID-SCAN SPECTROPHOTOMETERS

Block Engineering Model No.	Wavelength Range microns
I-4E	0.6 to 4.5
I-4I	1 to 7
I-4S	0.7 to 3.0
I-4SF	0.35 to 3.0
I-4T*	2 to 15
I-4TC	5 to 40
I-4TR	5 to 32
I-4TF	0.7 to 9.5
I-4L	0.40 to 1.1

*Block Engineering Model I-4T:

Scan rate, scans/sec	0.5, 1, 2, 3-1/2, and 6-1/2
Wavelength range, microns	2 to 15
Resolution, cm^{-1}	40
Readout	CRT, tape recorder, wave analyzer, recorder
Instrument type	Interferometer
Power requirements	115 v, ac; 10 watts
Ruggedness	Vibration-resistant
Optics	KRS-5 (TlBr-TlI)
Detector type	Thermistor or bolometer
Auxiliary equipment	Hewlett-Packard wave analyzer, No. 1895
Price, $	9225
Comments	Cell, source, and wave analyzer must be provided

Table 19

TABLE 20

TURBIDITY METERS

	Jacoby-Tarbox Model A
Line diameter, in.	1 to 6
Sample flow	Determined by maximum pressure and line diameter
Sample temperature, °F	To 200
Sample pressure, psi	To 150
Ambient temperatures, °F	To 110
Sample path, in.	To 36
Range, ppm	0 to 100, 0 to 150, 0 to 200, and 0 to 1000
Sensitivity	1 ppm at 0 to 1000 ppm (as diatomaceous earth)
Window materials	Pyrex, standard
Materials in contact	Pyrex, neoprene, SS
Readout	7-in. meter
Recorder	0 to 1 ma, dc
Remote operation, ft	To 100
Power required	110 v, 60 cps, 75 watts
Comments	Should be adaptable to cryogenics; windows available in quartz or Vycor with Teflon gasketing; available with double windows to prevent frosting

Table 20

TABLE 2

DENSITY

	Nuclear-Chicago Qualicon Model 506	Saunders-Roe Type 336	Ohmart Model ASR-3
Line diameter or connection	3/4-in. min, S-section; 3-in. min, through	--	3 in. (S-shaped)
Sample flow	← 0 & up →		
Sample temperature, $^\circ$F	To 200	--	Almost any
Sample pressure	← Determined by line →		
Temperature control	Measure or compensate	--	Provided
Range of measurement	Adjustable	--	Span: 0.025 to $\pm$0.0005 sgu
Accuracy	To 0.0001 sgu	$\pm$0.1%	$\pm$2% of scale
Materials in contact	Pipe	Pipe	300-series SS
Response time	Variable, 0.5 sec to minutes	10 to 100 sec	Variable, 10 to 50 sec
Readout	Panel meter	Recorder	Meter
Recorder	Available, -5 to 0 to +5 mv	Provided	Available, 0 to 10 or 0 to 50 mv
Explosion proof	Yes	--	Class I, Group D
Hazards	Radiation: <6 mr/hour; max, 100 mr/week	Radiation: <2 mr/hour; max, 100 mr/week	Radiation: <5 mr/hour; max, 100 mr/week
Source size, millicuries	25 to 500, Cs^{137}	25, Cs^{137}	50 to 300, Cs^{137}
Utilities	110 v, 50/60 cps, 150 watts	110 v, 50 cps, 250 watts	110 v, 60 cps, 100 watts
Maintenance	← No moving parts →		
Remote unit, ft	To 1000	--	350
Propellants analyzed	Solid-propellant submixes	--	Liquid N_2, little limitation
Price, $	3000	--	5500
Comments	Detector temperature 120 to 140°F	--	Detector temperature 0 to 130°F

* Not applicable.

TABLE 21

DENSITY METERS

Ohmart Model ASR-3	Industrial Nucleonics Accuray Model DH-3	Arcco Model R	Automation Products Dynatrol
n. (u-shaped)	1, 2, or 3 in.	1/4 in.	3/4-in. NPT
————→	Determined by line capability	1000 to 3000 ml/min	0 & up, flow guard for high flows
ost any	To 425	~-100 to +200	-420 to +300
————→	Determined by line capability	To 600 psi	Max. 3000 psig
vis.?	Compensation available, ±30°F, $595	Corrected	Correct or compensate
n: 0.025 to 5 .05 sgu	Adjustable	Range, 0.05 to 4; span desirable, 0.05 to 0.2	Span, 0.25
f scale	±0.0001 to ±0.003 sgu	±0.5%	±2%
- ries SS	Line	SS, as required	Line, Teflon-coated probe
isible, t 0 sec	Variable, 0.1 to 30 sec	~0.01 min	Very short
e	Signal only	Circular chart	Signal provided
ihle, 0 to or 0 to 50 mv	-5 to 0 to +5 mv	Provided	Available, 0 to 10 mv, dc
s. I. Group D	Available	No electrical connections	Yes
istion: m/hour; , 150 mr/week	<5 mr/hour	NA*	NA
t 500, Cs137	250, Sr	NA	NA
) v, 60 cps,) watts	110 v, 60 cps, 250 watts	NA	110 v, 60 cps
————→	Nil	Little	Virtually none
O	To about 1000	NA	Almost no limit
quid N2, little aitation	---	N2H4, NH3, N2O4, HNO3	LH2, LN2, LO2, et al.
OO	4345	600	1450
tector mperature to 130°F	Recorder extra	Avoid excessive vibration; change range, $35; change span, $170; large sample required	Range changes may require new sensor or new unit; viscosity changes affect readings

Table 21

	Hallikainen Model 1077	Precision Scientific Catalog No. 74359	Bendix Ultraviscoson	Automation Products Series 901
Line diameter	1/8-in. FPT in, 1-in. FPT out	--	3/8-in. NPT	3/4-in. NPT
Flow rate	64 ml/min (approx 1 gph)	70 cc/min (1 gph)	0 & up	0 & up, flow; an for high rate:
Sample temperature, $^\circ$F	Ambient to 450	32 to 210	-100 to 650	-420 to + 0
Temperature correction	Control to $\pm 0.005^\circ$C	Control	Compensated	Corre; or compensate
Sample pressure	5 to 300 psig	45 psig or greater	Vacuum to 1000 psi	To 3000 psi
Filtration	Provided	Required	Not required	Not usually required
Sample disposition	Returned	Return or disposal	←	
Materials in contact	SS, CURO, & Monel filter screens	Glass capillary, lines, meters	SS probe and plastic mounting	Lines and probe (probe may be Teflon-coated)
Record	See below	Recorder	Provided	Signal only
Recorder	Pneumatic recorder $200 extra	Furnished	Also 0 to 50 mv, dc	0 to 10 mv, dc
Response time	1.4 min	5 to 6 min	Immediate	Virtually instantaneous
Range of measurement	0 to 2500 cp	30 to 2500 SSU*	0 to 50,000 cp	10^{-1} to 10^{5} cp i 5 steps
Accuracy, %	1	0.5	1 (reproducibility, 1%)	2
Explosion proof	Yes	Class I, Group D, Division 1	Yes	Class I, Group D Division 1
Power required	110 or 220 v, 60 cps, 1400 watts	110 v, 60 cps, 1000 watts	110 v, 60 cps, 150 watts	110 v, 60 cps
Price, $	3800	6500	5235	1450
Comments	Price includes constant-temperature baths; additional utilities: air (20 psig) and water for cooling	Auxiliary pump needed to return sample to process stream or deliver it when pressure is <45 psig; maintenance, ~2 hours/week	Probe extends 4 in. into sample; requires "Z" configuration for small lines; must avoid strong magnetic fields	Probe is 5-1/4 i long

* SSU, Saybolt second units.

** $cp = KDU \sqrt{\dfrac{\rho(8.02 - \rho)}{7.02}}$, where ρ = specific gravity of fluid.

TABLE 22

VISCOMETERS

Pendix treviscoson	Automation Products Series 900F	Norcross Model M14	Brookfield Viscometran	Epprecht RM 15	Single-Float Model 1?
-in. NPT	3/4-in. NPT	1/2 in.	Inlet, 1-in. FPT; outlet, 2-in. FPT	3/8 in.	1-1/2 in. N?
..up	0 & up, flow guard for high rates	To 2 or 3 gpm	--	0 to 1 gpm	0.75 to 2.0
0 to 650	-420 to +300	To 650	To 160	0 to 1000	To 450
persated	Correct or compensate	Control or compensate	--	Control	Measure
uum to 0 psi	To 3000 psi	Vacuum to 300 psig	Vacuum to 100 psi	Atmospheric to 700 psi	To 90 psig
required	Not usually required	Desirable	--	Depends on particle size	Desirable
---	---	--- Returned ---	---	---	---
probe and stic mounting	Lines and probe (probe may be Teflon-coated)	303 & 304 SS	316 SS	18/8M stainless	SS, Teflon,
vided	Signal only	Recorder	--	Visual readout, no record provided	Visual
o o 50 mv, dc	0 to 10 mv, dc	Provided	Available	Extra, mv potentiometer	Available
ediate	Virtually instantaneous	1 or 2 min	--	Very rapid	Almost insta
o 50,000 cp	10^{-1} to 10^5 cp in 5 steps	10^{-1} to 10^6 cp	0-50 to 0-50,000 cp	1.2 to 10^7 cp	500 to 10,00 (span, 3:1
repro- ibility, 1%)	2	--	1 (repro- ducibility, 0.3%)	0.05	4 (reproduc
	Class I, Group D, Division 1	Class 1, Group D	--	No	Available
v, 60 cps,) watts	110 v, 60 cps	110 v, 60 cps, 3 amp	--	110 v, 60 cps	110 v, 60 c
5	1450	1600	945, recorder extra	1785	280
be extends n. into ple; requires configura- n for small es; must id strong netic fields	Probe is 5-1/4 in. long	Readings are intermittent; instrument is "self-cleaning"; may be able to do liquid H_2	--	Continuous meas- urement, but not really a process instrument; features 15 speeds	Two-float vi 3301; with c chart record 3315

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| Brookfield Viscometer | Epprecht RM 15 | Fischer & Porter | |
		Single-Float Viscorator Model 15B 1735	Auto Sampling Model 15A 1152
Inlet, 1-in. NPT; outlet, 2-in. NPT	3/8 in.	1-1/2 in. NPT	1-in. NPT
--	0 to 1 gpm	0.75 to 2.0 gpm	4 to 15 gpm
To 160	0 to 1000	To 450	To 400
--	Control	Measure	Compensation extra
Vacuum to 100 psi	Atmospheric to 700 psi	To 90 psig	To 150 psi
--	Depends on particle size	Desirable	Desirable
316 SS	18/8 stainless	SS, Teflon, glass	SS
--	Visual readout, no record provided	Visual	Magnetic follower
Available	Extra, mv potentiometer	Available	Available, 12-in. circular chart
--	Very rapid	Almost instantaneous	Almost instantaneous
0-50 to 0-50,000 cp	1.2 to 10^7 cp	500 to 10,000 KDU** (span, 3:1 to 6:1)	Size 4, 5 to 150 KDU; Size 6, 150 to 550 KDU;
1 (reproducibility, 0.3%)	0.05	4 (reproducibility, 1%)	2 to 4 (reproducibility, 1%)
--	No	Available	Available
--	110 v, 60 cps	110 v, 60 cps	110 v, 60 cps, if required
945, recorder extra	1785	280	1200
--	Continuous measurement, but not really a process instrument; features 15 speeds	Two-float viscorator, $301; with circular chart recorder, add $315	Pressure drop, about 7 psig; price with temperature compensation and recording, $2500

3

Table 22

TABLE 23

CONDUCTIVITY METERS

	Bailey Meter Model Cel-I	Bristol Co. Dynamaster	Foxboro Dynalog	Industrial Instruments RA-1, Solu-Meter	Leeds & Northrup No. 4985	Radiometer Type CDM 2
Conductivity range, micromhos	0-5 to 0-1000, 11 steps	0-10 to 0-20,000	0-0.5 to 0-2 x 10^6	As desired	(Typical: 0-100 micromhos/cm)	0-1.5 to 0-500, 14 steps
Accuracy, %	1-1/2	--	1 to 2	2	--	1 to 2
Data display	Circular chart	Circular chart	Circular chart	4-in. meter	4-in. meter	Meter
Temperature correction, °F	34-140, 64-190, manual or automatic	Manual or automatic	Manual or automatic for ambient ±30	32-122, 70-220, 150-275, manual or automatic	32-212, manual or automatic	Apparently not provided
Measurement frequency, cps	--	60	1000	60	60	70 or 3000, depending on conductivity
Remote recorder, ft	To 500	A few hundred	10, supplied	To 500	To 1000	--
Power required	115 v, 50/60 cps	120 v, 60 cps	115 v, 60 cps	115 v, 60 cps, 4 watts	120 v, 60 cps, 12 watts	110 v, 50/60 cps, 15 watts
Price, $	Recorder, 130; recorder-amplifier, 500	Recorder, 790	925, manual compensation + recorder	186 (portable, 196)	225	388, meter with 1 cell
Flow-cell electrode materials	Pt on Ni	Pt on Ni	Carbon or Pt	Pt/Ni	Pt on brass	--
Cell constants	0.01 to 2.0, 11 steps	0.01 to 2.0, 11 steps	Carbon: 0.01, 0.1, 1.0	0-0.01 to 2.0 micromhos, 11 steps	0.05 to 50, 7 steps	--
Line connections, in.	1-1/4 (1-3/4 insertion)	1/4 (1-3/4 insertion)	1-1/4 (6-1/2 insertion)	1-1/4 NPT	1-1/4 (3-1/4 insertion)	--
Materials in contact	316 SS, Pt/Ni, ceramic insulator	316 SS, Pt/Ni, ceramic insulator	SS, Kel-F, carbon	316 SS, ceramic, neoprene, Pt/Ni	304 SS, electrode	--
Sample pressure, psig	To 200 at 212°F	To 200 at 212°F	To 125	To 500 (psi)	To 200	--
Sample temperature, °F	To 212	To 212	To 300	To 212	To 200	--
Cell price, $	250 (SS flow cell with gate valve)	250 (SS flow cell with gate valve)	C, 85 each; Pt, 120 each	To 250	226 (Type 304 SS)	--
Comments	Industrial Instruments cell, Model Cel-I	Industrial Instruments cell, Model Cel-I	Carbon electrodes do not require Pt coating, may be replaced easily	--	Brass, $94	Jacks for recorder provided; any conductivity cell can be used with this meter

Table 23

TABLE 24

MICROWAVE SPECTROMETERS

	Tracerlab		
	MW-1	MW-2	MW-3
Type	Frequency-modulated	Stark-modulated	Stark-modulated, frequency-stabilized
Size of electronics, in.	20 x 18 x 60	20 x 18 x 72	20 x 18 x 84
Cell size, in.	144 x 6 x 6	144 x 6 x 6	144 x 10 x 10
Weight, lb	300	500	550
Power requirements	115 v, 50/60 cps, 1000 watts	115 v, 50/60 cps, 1500 watts	115 v, 50/60 cps, 1500 watts
Frequency range	Any 10-Gh range from 8 to 60 Gh	Any 10-Gh range from 8 to 60 Gh	8 to 60 Gh
Instrument sensitivity	(Approx 10 ppm) $\gamma_m = 10^{-7}$ cm^{-1}	(Approx 1 ppm) $\gamma_m = 10^{-9}$ cm^{-1}	(Approx 1 ppm) $\gamma_m = 10^{-10}$ cm^{-1}
Resolution, mc/sec	1	1	0.5
Accuracy, mc/sec	±15	±15	±0.05
Scanning	← Manual and electronic →		
Display	← Oscilloscope and X-Y recorder →		
Operating pressure	← 10^{-4} to 3 torr →		
Sample size, micrograms	← 100 →		

Table 24 (Sheet 1)

TABLE 25

GAS CHROMATOGRAPHY, SAMPLING VALVES

	Beckman 520-D	Greenbrier	Jarrell-Ash 26-731	Micro-Tek Series 6000	Osage Model 4SS
Type of sample	Liquid or gas	Liquid	Gas	Liquid	Liquid or gas
Sample size	0.75 microliter liquid to 50 cc gas	0.25 to 150 microliters	0.1 to 5 milliliters	0.25 to 10 microliters	0.5 to 3 microliters
Sample pressure	To 500 psi	To 500 psig	To 80 psi	To 1000 psi	1 mm Hg to 220 psia
Sample temperature, °C	To 225	To 200	To 200	To 220	To 200
Materials in contact	SS, Teflon	303 or 316 SS, impregnated Teflon	316 SS, Teflon	316 SS, Cr/316 SS, modified Teflon	SS, packing
Automatic or manual	Pneumatic	Manual or automatic	Manual	Manual	See price and comments below
Connection diameter, in.	1/8	1/8 NPT	1/8 Swagelok	1/8 Swagelok	1/8
Price, $	340 (4-port, SS)	250 to 350	415	295	295.50 (manual)
Comments	Used on 520-D chromatograph	Gas-sampling valve also available	-	-	Automatic, $225 extra; Change in sample size simple, new sleeves, $20; 4SS is 4-port valve

TABLE 26

GAS CHROMATOGRAPHY, VAPORIZER REGULATORS

	CEC 38-001A	Greenbrier PVR
Liquid-inlet size, in.	1/8 NPT	1/4 FPT
Liquid-inlet temperature	To 430°F	To 185°C
Liquid-inlet pressure	To 700 psi	10 to 450 psig
Vapor-outlet size, in.	1/8 NPT	1/4 FPT
Vapor-outlet pressure	8 to 30 psi	0 to 100 psig
Vapor-outlet rate, cc/min	2200, max	5 to 2000
Method of vaporization	Steam or electrical	Steam or electrical
Materials in contact	SS, Monel, Teflon	316 SS
Power required	None for steam vaporization	115 v, 5 amp for electrical vaporization
Price, $	325 (steam)	250 (steam), 300 (electrical)
Comments	Some sample is lost, so vent-gas disposal is required; steam connections: 1/2-in. NPT in, 1/4-in. NPT out	Disposal for vented gas required; steam connections: 1/2-in. FPT

Table 26

TABLE 27

GAS CHROMATOGRAPHS

	Consolidated 26-212A	Beckman 520-D	Greenbrier 818	Mine Safety 184
Connection size, in.	1/4	1/8	1/4 or 1/8	3/8
Sample size	Liquid or gas, 0.02 microliter to 1 milliliter	Liquid or gas, 0.5 microliter and up	Liquid, 1 to 60 microliters; gas, 3 to 50 milliliters	Gases
Sample flow	Max is calculated from other parameters	Gas, 50 to 100 cc/min; Liquid, 10 to 20 cc/min	60 cc/min	To 3 liters/min
Sample pressure, psi	To 80	To 500	25 (psig)	-
Sample temperature, °C	To 150	To 225	To 300	To 230
Number of streams	To 8	Standard, 10	1	1
Number of components	4 standard (to 9)	Standard, 24	To 4	4
Time for analysis, min	1 to 60	0.5 to 120	1 to 60	0.5 to 30
Programing	Cam	Magnetic tape or wheel	Cam	Cam or tape
Readout	Bargraph or chrometogram	Bargraph or other	Bargraph recorder	Bargraph or other
Column temperature	120 to 300°F	To 225°C	50 to 300°C ±0.01°C	120 to 450°F ±0.03°F

Table 27 (Sheet 1)

TABLE 27 (cont.)

	Consolidated 26-212A	Beckman 520-D	Greenbrier 818	Mine Safety 184
Materials in contact	SS (316, 304, 431), Teflon	SS, Teflon	304 SS, Viton A	SS, Teflon
Explosion proof	←————————— Yes —————————→			
Remote operation, ft	To 500	To 1000	1500	As needed
Power required	115 v, 60 cps, 1500 watts	115 v, 60 cps	115 v, 60 cps	115 v, 60 cps
Maintenance	←————————— Carrier gas —————————→			
Price, $	5100	5800 (1 stream, 4 components)	5000	4000
Comments	-	Wheel programing less expensive; column application approximately $500 extra, optional	-	-

Table 27 (Sheet 2)

TABLE 28

MASS SPECTROMETERS

	Bendix 17-210	CEC 21-620A	Picker MS-10
Spectrometer type	Velocity-focusing	Direction-focusing	Direction-focusing
Mass range	1 to 250 (recorder)	2 to 4 and 12 to 150	2 to 100
Sampling system	Standard: continuous gas analysis	Standard: continuous gas analysis	Standard: gas analysis
Sample requirement	Gas, 5 to 100 ml/min	Gas, 5 cc/min	0.25 cc/sec
Sample-line diameter, in.	3/8 SS	1/4 NPT SS	0.013 SS
Sample pressure	0.001 torr to atmospheric	To atmospheric	To atmospheric
Sample temperature, °C	Ambient	To 200	To 300
Response time	60 millisec	99% in 1 sec	1 sec
Accuracy, %	1	3 (precision, 0.5%)	-
Analysis time	10,000 scans/sec	30 min/scan	15 min/scan on each of 2 ranges
Record	Extra	Extra	Extra (meter provided)
Recorder	Available, 0 to 5 v, dc	Available, 0 to 10 mv, 1-sec response	Available, 0 to 10 mv, 1-sec response

Table 28 (Sheet 1)

TABLE 28 (cont.)

	Bendix 17-210	CEC 21-620A	Picker MS-10
Power required	115 v, 60 cps, 20 amp	115 v, 60 cps, 15 amp	220 v, 150 watts
Price, $	17,000 (Model 17)	16,900	4720 (standard)
Comments	Prices to $58,000; liquid handling $6560 extra; capable of monitoring 6 mass peaks or monitoring 5 peaks and scanning mass spectrum simultaneously; weight, 450 lb; unit resolution to mass 130	Liquid-sampling system extra; charcoal trap standard; peak selector, $1850 (7 sec on peak, 3 sec off, up to 6 peaks); weight, 800 lb; recorder, $1000; cooling water required	CO_2 cold trap; essentially a leak detector; 2% resolution at mass 40

Table 28 (Sheet 2)

TABLE 29

WINDOW MATERIALS

	Sapphire Al$_2$O$_3$	Fused Silica SiO$_2$	Spinel MgO · 3.5 Al$_2$O$_3$	Rutile TiO$_2$	MgF$_2$ (Irtran-1)	CaF$_2$ (Irtran-3)	BaF$_2$	ZnS (Irtran-2)	ZnSe (Irtran-4)
Transmission limits, microns	0.17 to 6.5	0.2 to 4.5	0.9 to 6.0	0.43 to 6.2	0.11 to 7.5	0.13 to 12.0	0.15 to 15.0	2 to 14	1 to 13.4
Refractive index	1.83 to 1.59	1.48 to 1.41	1.74 to 1.72	2.85 to 2.20	1.38 to 1.51	1.44 to 1.32	1.51 to 1.41	2.28 to 2.15	2.50 to 2.40
Knoop hardness	1370	461	1140	879	576	158.3	82	354	250
Thermal coefficient (× in./in.)	5.0, 6.7	0.5	5 (40°C)	7.14, 9.19 (40CC)	18.8, 13.1	24 (20 to 50°C)	--	--	--
Density or specific gravity	3.98	2.20	3.61	4.25	3.18 (25°C)	3.179 (25°C)	4.83 (26°C)	4.088 (25°C)	5.4
Dielectric constant	10.55	3.78	8 to 9	160, 200	4.87	6.76	7.33	--	--
Crystal system	Hexagonal	--	Cubic	Tetragonal	Tetragonal	Cubic	Cubic	--	--
Max diameter available, in.		18	1-1/4	--	6	6	6	6	6
Max thickness available, in.	--	--	--	--	3	1/2	--	--	--
Temperature range, °C	--	--	--	--	To 900	-200 to 1000	--	To 800	To 300
Solubility	Short time with F, ClF$_3$	Soluble in HF	--	Soluble in conc H$_2$SO$_4$	--	Soluble in ammonia solutions	Soluble in acids, NH$_4$Cl solutions	Attacked by oxidizers	--
Manufacturer	Linde, Keller	Corning	--	Linde	Eastman Kodak	Harshaw, Optovac, Isomet, Keller, Kodak	Harshaw, Isomet, Isomet, Keller	Kodak	Kodak
	1/8	1/4	--	--	1/8	--	--	1/8	(4 in)
			--	--	2	--	--	4	14
	4	4	--	--	14	--	--	34	34
	6	--	--	--	--	40	6	--	--
	--	1/4 × 3 in. grooves.	less no longer avail. Prism drive in. in diameter by 1/2 in. long across flats	Scale 1/8 in. in diameter by 1/2 in. long across flats	--	Used in IR and UV, IR spectro- photometric analysis	--	--	--

Table 29

TABLE 30

MANUFACTURERS AND REPRESENTATIVES

Manufacturer No.	Name and Address
	A. Flow and Liquid-Level Indicators
1	Jerguson Gage & Valve Co., 114 Fellsway, Somerville 45, Mass.
2	Penberthy Injector Co., Detroit 2, Mich.
3	Crane Co., 836 S. Michigan Ave., Chicago 5, Ill.
4	Strahman Valves, Inc., 16 Hudson St., New York, N.Y.
5	Mason-Neilan Regulator Co., 1184 Adams St., Boston 24, Mass.
6	Bailey Meter Co., 1057 Ivanhoe Rd., Cleveland 10, Ohio
7	Bristol Co., 105 Bristol Rd., Waterbury 20, Conn.
8	Mercoid Corp., 4201 Belmont Ave., Chicago 41, Ill.
9	Foxboro Instrument Co., 1212 S. Garfield, Los Angeles, Calif.
10	Fisher Governor Co., Marshalltown, Iowa
11	Liquidometer Corp., Long Island City 1, N.Y.
12	Fielden Electronics, Inc., Huntington, N.Y.
13	Robertshaw Fulton Controls Co., Knoxville 1, Tenn.
14	United Engineers, Inc., 820-824 E. Sixth St., Tulsa, Okla.
15	Mine Safety Appliances Co., Pittsburgh 8, Penn.
16	Tracerlab, Inc., 1601 Trapelo Rd., Waltham 54, Mass.
17	Wallace & Tiernan, 25 Main St., Belleville 9, N.J.
18	Barton Instrument Co., 580 S. Monterey Pass Rd., Monterey Park, Calif.
19	Pace Engineering Co., 13035 Saticoy, North Hollywood, Calif.
20	Toledo Scales Co., 1010 Telegraph Rd., Toledo, Ohio
21	Dynametrics Corp., 1 N.W. Industrial Park, Burlington, Mass.
22	Cherry-Burrell Corp., Cedar Rapids, Iowa
23	Daniel Orifice Corp., 3352 Union Pacific Ave., Los Angeles 23, Calif.
24	Nordstrom Valve Division, Rockwell Manufacturing Co., Pittsburgh 8, Penn.
25	Infilco, Inc., Tucson, Ariz.
26	The Permutit Co., 50 West 44th St., New York 36, N.Y.

Table 30 (Sheet 1)

TABLE 30 (cont.)

Manufacturer No.	Name and Address

A. Flow and Liquid-Level Indicators (cont.)

27	Aerojet-General Corp., Box 296, Azusa, Calif.
28	Buffalo Meter Co., Dept. CC, 2917 Maine St., Buffalo 14, N.Y.
29	Lapp Process Equipment Division, 5000 Gilbert St., Leroy, N.Y.
30	Neptune Meter Co., 47-25 34th St., Long Island City 1, N.Y.
31	Brooks Instrument Co., Inc., 7300 W. Vine St., Hatfield, Penn.
32	Schutte and Koerting Co., 2229 State Rd., Cornwells Height, Penn.
33	Black, Sivalls and Bryson, Inc., Kansas City, Kans.
34	Potter Aeronautical Corp., P.O. Box 1123, Union, N.H.
35	Fischer & Porter Co., 130 Orangethorpe Way, Anaheim, Calif.
36	Waugh Engineering, 7842 Burnet Ave., Van Nuys, Calif.
37	Hydrapoise, Inc., 230 S. Wells Fargo Dr., Scottsdale, Ariz.

B. Centrifugal Pumps

1	Paul Chemical Co., 6750 Caballero Blvd., Buena Park, Calif.
2	Turbocraft, Inc., 1946 S. Myrtle Ave., Monrovia, Calif.
3	Hydro-Aire Co., 3000 Winona Ave., Burbank, Calif.

C. Vacuum-Jacketed Valves

1	Security Valve Co., 909 El Centro, South Pasadena, Calif.
2	Flodyne Controls, Inc., Linden, N.J.
3	The Annin Co., 1040 S. Vail Ave., Montebello, Calif.
4	Kieley and Mueller, Middletown, N.Y.
5	Valcor Engineering Corp., 365 Carnegie Ave., Kenilworth, N.J.
6	Paul Chemical Co., 6750 Caballero Blvd., Buena Park, Calif.

Table 30 (Sheet 2)

TABLE 30 (cont.)

Manufacturer No.	Name and Address

D. Vacuum-Jacketed Piping

1   Aeroquip Corp., Marman Division, 11214 Exposition Blvd.,
La Angeles 65, Calif.

2   Oman-Mason Corp., 16611 Ventura Blvd., Encino, Calif.

3   Uni-Flex Manufacturing and Engineering, Inc.,
5545 E. Slauson Ave., Los Angeles 22, Calif.

E. Gold-Cobalt Thermocouples

1   Sigmund Cohn Corp., 121 S. Columbus Ave., Mt. Vernon, N.Y.

F. Cast Window Housing

1   Arwood Corp., Mercast Division, 2620 First St.,
La Verne, Calif.

2   Turbo Cast, Inc., 1860 E. Gage Ave., Los Angeles 1, Calif.

G. Multiwall Vessels

1   Standard Steel Corp., 5001 S. Boyle, Vernon, Calif.

2   Chicago Bridge and Iron Co., Salt Lake City, Utah

H. Vacuum-Jacketed Filters

1   Purolator Products, Inc., Rahway, N.J.

2   Circle Seal Development Corp., Anaheim, Calif.

I. Activation-Analysis Equipment

1   Aerojet-General Nucleonics, Box 77, San Ramon, Calif.

2   General Atomics, Box 608, San Diego 12, Calif.

3   High Voltage Engineering Corp., Box 98, Burlington, Mass.

4   Isotope Specialties Co., 170 W. Providencia,
Burbank, Calif (VI 9-2273)

5   Nuclear Chicago Corp., 1063 Colorado Blvd.,
Los Angeles 41, Calif (CL 5-4711)

6   Philips Electronic Instruments, 750 S. Fulton Ave.,
Mt. Vernon, N.Y. Rep: Braun Chemical Co., 1363 S. Bonnie
Beach, Los Angeles 54, Calif. (AN 9-9311, Mr. Phil Evans)

Table 30 (Sheet 3)

TABLE 30 (cont.)

Manufacturer No.	Name and Address

I. Activation-Analysis Equipment (cont.)

7   Picker X-Ray Corp., 710 S. Lake, Los Angeles 57, Calif.
(DU 8-2366)

8   Texas Nuclear Corp., Box 9267, Austin, Tex.

9   U.S. Nuclear, 801 N. Lake St., Burbank, Calif. (VI 9-6176)

J. Particle-Size Analyzers

1   Coulter Electronics, 5227 N. Kenmore, Chicago 40, Ill.
Rep: Bogart-Bullock Corp., 6010 S. Normandie Ave.,
Los Angeles 44, Calif. (PL 1-4173)

2   High Accuracy Products Corp., 149 W. First,
Claremont, Calif. (NA 4-3676)

3   Phoenix Precision Instruments Co., 3805 N. Fifth,
Philadelphia 40, Penn.

4   Royco Instruments, Inc., 440 Olive St., Palo Alto, Calif.
(DA 6-1831), or Los Angeles 65, Calif. (CL 7-5340)

5   Sperry Products Co., 3501 Lomita Blvd., Torrance, Calif.
(775-3084)

K. High-Speed Photography Equipment

1   Beckman & Whitley, San Carlos, Calif.

2   Bell & Howell Co., 7100 McCormick Rd., Chicago 45, Ill.

3   Edgerton, Germeshausen and Grier, 160 Brookline Ave.,
Boston 15, Mass.
Rep: J. T. Hill Co., 420 S. Pine St., San Gabriel, Calif.
(CU 3-6555)

4   Electro-Optical Instruments, Inc., 922 S. Myrt.e Ave.,
Monrovia, Calif. (359-9391)

5   Fairchild Camera and Instrument Corp., 580 Midland Ave.,
Yonkers, N.Y.
Rep: Gordon Enterprises, 5362 N. Cahuenga Blvd.,
North Hollywood, Calif. (TR 7-2135)

6   General Metallic Parts Ltd., 16 Milford Ave.,
Toronto 15, Ont., Canada
Rep: James L. McCoy Co., 940 Alma St., Glendale 2, Calif.
(CI 6-2134)

Table 30 (Sheet 4)

TABLE 30 (cont.)

Manufacturer No.	Name and Address

K.   High-Speed Photography Equipment (cont.)

7   Photo-Sonics, Inc., 820 S. Mariposa St., Burbank, Calif. (VI 9-6251)

8   Revere Camera Co., 850 Hudson Ave., Rochester 21, N.Y.
Rep: Wollensak Division, through Minnesota Mining and Manufacturing, 6023 S. Garfield Ave., Los Angeles 22, Calif. (RA 3-6641, Mr. Charles Wade)

9   Unilectron, Inc., 129 Binney St., Cambridge 42, Mass.

L.   Water Analyzers

1   American Meter Co., 301 N. Gilbert, Fullerton, Calif. (MA 8-8387)

2   Beckman Instruments, Inc., 2500 Harbor Blvd., Fullerton, Calif. (OW 1-0841)

3   Boonton Polytechnic, Box 227, Rockaway, N.J.

4   Burrows Equipment Co., 1316 N. Sherman Ave., Evanston, Ill.

5   Consolidated Electrodynamics Corp., 490 E. Walnut St., Pasadena, Calif. (SY 5-9753)

6   Foxboro Instrument Co., 1212 S. Garfield, Alhambra, Calif. (CU 3-6693)

7   Instruments, Inc., 3101 Sand Spring Rd., Tulsa, Okla.
Rep: M. D. Schriver Co., 3155 Rosemead Blvd., Rosemead, Calif. (CU 3-7231)

8   Manufacturers Engineering and Equipment Co., 250 Titus Ave., Warrington, Penn.

9   Mine Safety Appliances Co., 115 W. 25th St., Los Angeles, Calif. (RI 7-9567)

10   Moisture Register Co., 1510 W. Chestnut St., Alhambra, Calif. (CU 3-3143)

11   Nuclear Chicago Corp., 1063 Colorado Blvd., Los Angeles 41, Calif. (CL 5-4711)

12   Robertshaw-Fulton Controls Co., Santa Ana Freeway at Euclid Ave., Anaheim, Calif. (KE 5-8151)

13   Westberg Manufacturing Co., Box 239, Napa, Calif.

Table 30 (Sheet 5)

TABLE 30 (cont.)

Manufacturer No.	Name and Address

M.   Specific Electrodes

1	Analytic Systems Co., 980 N. Fair Oaks Ave., Pasadena, Calif. (MU 1-6634)
2	Analytical Measurements, Inc., 490 Morris Ave., Summit, N.J.
3	Beckman Instruments, Inc., 2500 Harbor Blvd, Fullerton, Calif. (OW 1-0841)
4	Greenbrier Instruments, Box 68, Ronceverte, W. Va. Rep: Bogart-Bullock Corp., 6010 S. Normandie Ave., Los Angeles 44, Calif. (PL 1-4173)
5	Leeds & Northrup Co., 1190 Monterey Pass Rd., Monterey Park, Calif. (AN 9-3191)
6	Mine Safety Appliances Co., 115 W. 25th St., Los Angeles, Calif. (RI 7-9567)
7	Yellow Springs Instrument Co., Box 106, Yellow Springs, Ohio

N.   Robot Chemists

1	Hagan Chemicals and Controls, Inc., 3040 Tweedy Blvd., South Gate, Calif. (LO 7-2384)
2	Milton Roy Co., 526 N. Garfield Ave., Monterey Park, Calif. (CU 3-7674)
3	Research Specialties Co., 200 S. Garrard Blvd., Richmond, Calif.
4	Technicon Controls, Inc., Saw Mill River Rd., Chauncey, N.Y.

O.   Flame Photometers

1	Technicon Controls, Inc., Saw Mill River Rd., Chauncey, N.Y.
2	Waters Associates, 47 Franklin St., Framingham, Mass. Rep: Bogart-Bullock Corp., 6010 S. Normandie, Los Angeles 44, Calif. (PL 1-4173)

P.   X-Ray Fluorescence Spectrometers

1	Applied Research Laboratories, 3717 Park Pl., Glendale, Calif. (CH 5-5524)
2	General Electric Co., 1225 N. Vermont, Los Angeles, Calif. (NO 3-9367)

Table 30 (Sheet 6)

TABLE 30 (cont.)

Manufacturer No.	Name and Address
	P. X-Ray Fluorescence Spectrometers (cont.)
3	Philips Electronic Instruments, 750 S. Fulton Ave., Mt. Vernon, N.Y. Rep: Braun Chemical Co., 1363 S. Bonnie Beach, Los Angeles 54, Calif. (AN 9-9311, Mr. Phil Evans)
	Q. Polarimeters
1	The Bendix Corp., 3130 Wasson Rd., Cincinnati, Ohio Rep: E. H. Sargent, 1617 E. Ball Rd., Anaheim, Calif. (MA 5-2481)
	R. Refractometers
1	Barnes Engineering Co., 30 Commerce Rd., Stamford, Conn. Rep: Costello & Co., 2740 S. La Cienega Blvd., Los Angeles 34, Calif. (UP 0-8537)
2	Daystrom, Inc., 736 Monterey Pass Rd., Monterey Park, Calif. (AN 8-9271)
3	Mine Safety Appliances Co., 115 W. 25th St., Los Angeles, Calif. (RI 7-9567)
4	Optics Technology, Inc., 248 Harbor Blvd., Belmont, Calif. Rep: Abbott Instrument and Engineering Co., 10513 Santa Monica Blvd, Los Angeles 25, Calif. (GR 4-5310)
5	Waters Associates, 47 Franklin St., Framingham, Mass. Rep: Bogart-Bullock Corp., 6010 S. Normandie, Los Angeles 44, Calif. (PL 1-4173)
	S. Colorimeters
1	Beckman Instruments, Inc., 2500 Harbor Blvd, Fullerton, Calif. (OW 1-0841)
2	Hallikainen Instruments, 1341 Seventh St., Berkeley 10, Calif. Rep: Bogart-Bullock Corp., 6010 S. Normandie, Los Angeles 44, Calif. (PL 1-4173)
3	Photovolt Corp., 1115 Broadway, New York 10, N.Y.
	T. Nondispersive Photometers
1	Analytic Systems Co., 980 N. Fair Oaks Ave., Pasadena, Calif. (MU 1-6634)

Table 30 (Sheet 7)

TABLE 30 (cont.)

Manufacturer No.	Name and Address

T.   Nondispersive Photometers (cont.)

2   Beckman Instruments, Inc., 2500 Harbor Blvd.,
Fullerton, Calif. (OW 1-0841)

3   E. I. du Pont de Nemours & Co., Inc., 1007 Market St.,
Wilmington 98, Del.

4   Hallikainen Instruments, 1341 Seventh St., Berkeley 10, Calif.
Rep: Bogart-Bullock Corp., 6010 S. Normandie,
Los Angeles 44, Calif. (PL 1-4173)

5   Leeds & Northrup Co., 1190 Monterey Pass Rd.,
Monterey Park, Calif. (AN 9-3191)

6   Mine Safety Appliances Co., 115 West 25th St.,
Los Angeles, Calif (RI 7-9567)

U.   Rapid-Scan Spectrophotometers

1   American Optical Co., 1433 Cole Pl., Los Angeles 28, Calif.
(HO 3-4161)

2   Beckman Instruments, Inc., 2500 Harbor Blvd.,
Fullerton, Calif. (OW 1-0841)

3   Block Engineering, 385 Putnam Ave., Cambridge 39, Mass.

V.   Turbidity Meters

1   Jacoby-Tarbox Corp., 808 Nepperhan Ave., Yonkers 3, N.Y.
(914 YO 5-8400)

W.   Density Meters

1   Arcco Instrument Co., 7144 E. Condor St.,
Los Angeles 22, Calif (OV 5-7491)

2   Automation Products, 3032 Max Roy, Houston, Tex.
Rep: Barton Sales, 350 S. Atlantic Blvd.,
Monterey Park, Calif. (CU 3-6501)

3   Industrial Nucleonics Corp., 650 Ackerman Rd.,
Columbus 2, Ohio
Rep: Mr. Merrill Luthman, 788 Hiramar Terrace,
Belmont, Calif. (Phone: DIamond 4-8981, San Mateo,
Calif.)

4   Nuclear-Chicago Corp., 1063 Colorado Blvd.,
Los Angeles 41, Calif. (CL 5-4711)

Table 30 (Sheet 8)

TABLE 30 (cont.)

Manufacturer No.	Name and Address

W. Density Meters (cont.)

5 The Ohmart Corp., 4241 Allendorf Dr., Cincinnati 9, Ohio
Rep: Crown Berkley Engineering Co., 2439 Riverside Dr.,
Los Angeles 39, Calif. (NO 5-1251)

6 Saunders-Roe & Nuclear Enterprises Ltd.
Rep: Nuclear Enterprises Ltd., 550 Berry St.,
Winnipeg 21, Man., Canada

X. Viscometers

1 Automation Products, 3032 Max Roy, Houston, Tex.
Rep: Barton Sales, 350 S. Atlantic Blvd.,
Monterey Park, Calif. (CU 3-6501)

2 The Bendix Corp., 3130 Wasson Rd., Cincinnati, Ohio
Rep: E. H. Sargent, 1617 E. Ball Rd., Anaheim, Calif.
(MA 5-2481)

3 Brookfield Engineering Laboratories, 15 Cushing St.,
Stoughton, Mass.

4 J. W. Fecker Division of American Optical Co.,
6592 Hamilton Ave., Pittsburgh 6, Penn.

5 Fischer & Porter Co., 970 S. Goodrich Blvd.,
Los Angeles 22, Calif. (685-6304)

6 Hallikainen Instruments, 1341 Seventh St., Berkeley 10, Calif.
Rep: Bogart-Bullock Corp., 6010 S. Normandie Ave.,
Los Angeles 44, Calif. (PL 1-4173)

7 Norcross Corp., 247 Newtonville Ave., Newton 58, Mass.
Rep: Jensen Instrument Co., 1919 Beverly Blvd.,
Los Angeles 57, Calif. (DU 8-2248)

8 Precision Scientific Development Co., 3737 W. Cortland St.,
Chicago 47, Ill.

Y. Conductivity Meters

1 Bailey Meter Co., 504 S. Monterey Pass Rd., Monterey Park,
Calif. (CU 3-1187)

2 Bristol Co., 6800 E. Acco St., Los Angeles 22, Calif.
(RA 3-9751)

3 Foxboro Instrument Co., 1212 S. Garfield, Alhambra, Calif.
(CU 3-6693)

Table 30 (Sheet 9)

TABLE 30 (cont.)

Manufacturer No.	Name and Address

Y. Conductivity Meters (cont.)

4 — Industrial Instruments, Inc., 89 Commerce Rd.,
Cedar Grove, N.J.
Rep: G. H. Vaughan Co., 2366 E. Foothill Blvd.,
      Pasadena, Calif. (MU 1-4511)

5 — Leeds & Northrup Co., 1190 Monterey Pass Rd.,
Monterey Park, Calif. (AN 9-3191)

6 — Radiometer of Copenhagen, Denmark
Rep: Electro-Medical Engineering Co., 703 Main St.,
      Burbank, Calif. (TH 8-9344)

Z. Microwave Equipment

1 — Southwest Research Institute, 8500 Culebra,
San Antonio, Tex.

2 — Tracerlab, 1601 Trapelo Rd., Waltham 54, Mass.

AA. Gas Chromatographs

1 — Beckman Instruments, Inc., 2500 Harbor Blvd.,
Fullerton, Calif. (OW 1-0841)

2 — Consolidated Electrodynamics Corp., 490 E. Walnut St.,
Pasadena, Calif. (SY 5-9753)

3 — Greenbrier Instruments, Box 68, Ronceverte, W. Va.
Rep: Bogart-Bullock Corp., 6010 S. Normandie Ave.,
      Los Angeles, Calif. (PL 1-4173)

4 — Jarrell-Ash Co., 26 Farwell St., Newtonville 60, Mass.

5 — Micro-Tek Instruments, 550 Oak Villa Rd., Baton Rouge, La.

6 — Mine Safety Appliances Co., 115 W. 25th St.,
Los Angeles, Calif. (RI 7-9567)

7 — Osage Instrument Co., 7366 Moline, Houston 17, Tex.
Rep: Barber-Colman Co., 750 Monterey Pass Rd.,
      Monterey Park, Calif. (AN 8-9251)

BB. Mass Spectrometers

1 — The Bendix Corp., Mr. Harry Madden, Downey, Calif. (923-5888)

2 — Consolidated Electrodynamics Corp., 490 E. Walnut St.,
Pasadena, Calif. (SY 5-9753)

3 — Picker X-Ray Corp., 710 S. Lake, Los Angeles 57, Calif.
(DU 8-2366)

Table 30 (Sheet 10)

TABLE 30 (cont.)

Manufacturer No.	Name and Address
	CC. Window Materials
1	Corning Glass Works, 420 S. Euclid, Anaheim, Calif. (MA 8-7229)
2	Eastman Kodak Co., 400 Plymouth Ave. N., Rochester 4, N.Y.
3	Harshaw Chemical Co., 1945 E. 97th St., Cleveland 6, Ohio
4	Hofman Laboratories, 5 Evans Terminal, Hillside, N.J. Sub: Paul Chemical Co., 6750 Caballero Blvd., Buena Park, Calif. (LA 1-2917)
5	Isomet Corp., 433 Commercial Ave., Palisades Park, N.J.
6	Limit Research Corp., 557 Post Rd., Darien, Conn.
7	Linde Co., 2770 Leonis Blvd., Los Angeles 58, Calif. (LU 3-3061)
8	Meller, Adolph Co., Box 6001, Providence, R.I.
9	National Aeronautics and Space Administration, Lewis Research Center, 21000 Brookpark Rd., Cleveland 35, Ohio
10	Optovac, 61 Summer St., North Brookfield, Mass.

Table 30 (Sheet 11)

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